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RELIABILITY, MAINTAINABILITY, AND PERFORMANCE ISSUES IN HYDRAULIC SYSTEM DESIGN

Boeing Vertol Company
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EUSTIS DIRECTORATE POSITION STATEMENT

This Directorate concurs in the findings of this report and recommends the use of this information as an assessment of significant issues in the design and development of hydraulic systems for rotary-wing aircraft.

The report documents the results of a study which assessed the state of the art in the design and operation of hydraulic systems on Army helicopters. The hydraulic system on the CH-47C aircraft served as a baseline for the purpose of comparing advanced system concepts. It was chosen because it does not bias the study either for or against very high pressure systems. The study deals with the problems associated with the design and operation of helicopter hydraulic systems in a generic sense. The assessment of advanced system concepts is considered to be valid; however, the reader is cautioned that these assessments do relate back to the baseline aircraft and might not be valid for aircraft of different type or size. The report is considered to be valuable for its assessment of the state of the art in current inventory aircraft and its identification of significant issues to be considered in the design and development of new systems.

The technical monitor for this program was Mr. Gene A. Birocco of Military Operations Technology Division.

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The program objective was to compare an Advanced Conventional Pressure (ACP) 3000-psi helicopter hydraulic system to a Very High Pressure (VHP) 8000-psi system in terms of benefits, drawbacks, and development requirements. The work included the assessment of the state of the art of helicopter hydraulic systems, the development of an evaluation methodology, and the selection of a helicopter to serve as a baseline and as a over

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vehicle for the ACP and VHP designs.

SUMMARY

The program objective was to conduct a detailed assessment of the state of the art in Army helicopter hydraulic system design and to recommend an approach to attacking the problem areas in current systems. The program included application of Very High Pressure (VHP) technology to the design of an aircraft hydraulic system, and a comparison of the payoffs resulting from various system pressures.

The CH-47C was selected as the baseline aircraft because there were large numbers in the U. S. Army inventory, all of the common hydraulic systems used in helicopters were represented, and design data was readily available. The evaluation methodology developed was: to design Advanced Conventional Pressure (ACP) and VHP systems, keeping system performance constant; and then to perform qualitative and quantitative evaluations of reliability, maintainability, safety, vulnerability, volume, cost, and weight.

The state-of-the-art assessment determined that the major technical problems of Army helicopter hydraulic systems, with the possible exception of actuator seal life, can be solved using technology that is available today. However, the unvented seal concept that has been used by the Russians may provide a solution to the seal life problem within the present technological base. Problems that require further development are:

PRESENT PROBLEMS THAT REQUIRE FURTHER DEVELOPMENT WITHIN THE STATE OF THE ART

SUMMARY

PROBLEMS	EXISTING SOLUTIONS	FURTHER WORK
Plumbing leaks impact reliability, maintainability, safety and cost.	Reduce leak points by component modularization and by swaging line connections. Use new fitting designs.	Develop program to optimize usage of modularization and diagnostics.
Fault isolation difficulties result in false removals that impact maintainability and cost.	Design systems with better fault isolation characteristics including new diagnostics.	
Seal life impacts reliability, maintainability, safety, and cost.	Improved (5-15 micron) filtration to reduce contamination; use state-of-the-art scraper rings, and include actuator seal boots for extreme environmental situations.	Develop seal concepts and materials. Investigate relationship between seal wear and contamination in the range of 5 microns and lower. Develop improved scraper seals.

The results of the program evaluations for the three flight control hydraulic systems are compared below:

HYDRAULIC SYSTEM EVALUATION SUMMARY

	Baseline system	ACP system	VHP system
Reliability	29.462 Failures / 10^3 FH	43% better	43% better
Maintainability	87.834 MMH / 10^3 FH	30% better	25% better
Safety	λ=2.0172326	99% better	99% better
Vulnerability	2.45ft^2 ESVA[a]	37% better	48% better
Cost development	1.0	10% costlier	20% costlier
Cost manufacturing	1.0	20% costlier	10% costlier
Weight	537.7 lbs	11% heavier	1% lighter

a = Equivalent Singly Vulnerable Area

In the evaluations performed in this program, VHP systems were determined to offer advantages over the baseline and ACP systems for most helicopter applications. VHP technology offers a potential for reducing hydraulic system weight and improving combat survivability. A VHP system is less vulnerable because higher pressure allows smaller sized components than a 3000-psi system. The VHP system discussed in this report was only slightly lighter than the baseline system because the baseline system was designed with more emphasis on weight savings and less stress on reliability and maintainability features. The Very High Pressure system is significantly lighter than the Advanced Conventional Pressure (ACP) system. Weight savings are determined by many factors, but primarily by the system power level required. Higher power systems show more potential for weight savings. The baseline helicopter lower controls operate at very low power levels. This necessitates the use of 1500 psi in that portion of the system in order to provide flow rates that allow proper control valve manufacture. Since the VHP, ACP, and baseline systems all used 1500 psi, VHP weight savings in the lower controls were minimal. This slightly reduced the overall weight savings of the VHP system when measured as a percentage.

The major recommendations of this study are as follows:

- Develop a methodology to optimize usage of modularization and diagnostics.
- Perform 3000-psi laboratory testing of the multiple unvented seal concept, discussed in Appendix C, to assess its potential for improving actuator reliability.
- Continue the Army VHP effort, concentrating on seal development to achieve adequate VHP actuator seal life for helicopter operations.

PREFACE

This report documents work performed by the Boeing Vertol Company under Contract DAAJ02-75-C-0020. The program was under the technical cognizance of Mr. Gene Birocco from the Military Operations Technology Division of the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia.

Messrs. J. Demarchi, B. Holland, and R. Haning from the Columbus Aircraft Division of Rockwell International Corporation participated in this program under a subcontract to the Boeing Vertol Company. They were responsible for the VHP (8000 psi) system design, and contributed much of the information concerning its developmental history and requirements. Their efforts were documented in Rockwell International Corporation Report NR76H-81, dated October 1976.

The authors wish to acknowledge contributions to this program by the following Boeing Vertol Company personnel: Messrs. Y. Badri Nath, J. Gonsalves, W. Schmidt, O. Greenwood, and T. Brady.

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HELICOPTER HYDRAULIC SYSTEMS STATE OF THE ART

INTRODUCTION

The evolution of helicopter hydraulic systems can best be described by segregating the systems into "generations". The first generation of helicopter hydraulic systems to reach reasonable production and service included the H-19, H-25, and H-21. This generation had single-boost flight control hydraulic systems. Hydraulic boost had been introduced because gross weight and rotor vibratory feedback loads reached a level that exceeded pilot capability to comfortably control the helicopter. Most first-generation helicopters were controllable without hydraulic boost, so no backup systems were required other than the mechanical-type controls that had been used in lighter helicopters up to that time. Whenever the single hydraulic system was disabled, the pilot merely flew the helicopter to the nearest airfield, using the mechanical system. A certain amount of normal leakage from hydraulic components was tolerated, and if gross leaks or other hydraulic system malfunctions occurred, the result was discomfort but little danger.

Second-generation helicopter hydraulic systems (the H-46, H-47, and H-54) included drastically revised flight control responsibilities and many additional utility functions. These helicopters were not controllable without hydraulic boost; therefore, a second hydraulic system was included to provide the required backup function. Both first- and second-generation helicopter hydraulic systems were classified as single fail-safe; i.e., the mission was aborted after a single power-assist failure, but the helicopter could be landed safely. The second generation brought basic changes in the state of the art of helicopter hydraulic systems. System pressure levels were increased from approximately 1000 psi to 3000 psi for flight controls, and to 4000 psi for specific utility functions on certain helicopters. In addition, extensive utility hydraulic system duties were added, such as winches, ramps, brakes, and APU starting mechanisms. This proliferation of subsystems brought with it certain problems. Earlier concepts prevailed; hydraulic systems were scattered through the aircraft with clusters of components and tubes at various locations.

Third-generation helicopter hydraulic systems (Utility Tactical Transport Aircraft System (UTTAS) and Advanced Attack Helicopter (AAH) programs) are just entering service. These systems are characterized by the requirement to be single fail-operational; that is, they have mission-safety for a single power-assist failure and fail-safety for a second

power-assist failure. This requires increased redundancy (three flight control hydraulic power sources) with a considerable increase in complexity.

HYDRAULIC SYSTEM RELIABILITY

Introduction

Figure 1 shows hydraulic system reliability for typical helicopters of the three generations. As would be expected, the greater reliability improvement attained, the more difficult it becomes to maintain the rate of improvement. Reliability increases between generations can be attributed to many factors, including:

1. Seal material and configuration improvements.
2. Hydraulic tube, hose, fitting, and clamp improvements.
3. Filtration technology improvements.
4. Increased design experience.
5. Increased user experience.

Third-generation systems have not accumulated extensive field experience; therefore, second-generation systems were studied. It was then necessary to predict how well the third-generation improvements would solve traditional problems, and what could be done to improve upon those solutions. While helicopters within one generation share the same seal, tubing and filtration technology, a great number of reliability problems are peculiar to individual aircraft hydraulic systems. There are many reasons for this, including less attention being paid to one segment of the design effort, a miscalculation of some system or airframe parameter, or an unanticipated outside influence. This analysis will attempt to concentrate on generic problems rather than those problems peculiar to individual systems.

Typical Problem Areas

A previous study (Reference 1) concluded that UH-1F hydraulic failures can be categorized into three main reliability problems:

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[1]Barrett, L. D., and Aronson, R. B., RELIABILITY AND MAINTAINABILITY PROGRAM FOR SELECTED SUBSYSTEMS AND COMPONENTS OF CH-47 AND UH-1 HELICOPTERS, The Boeing Vertol Company, Document D210-10846-1, U. S. Army Aviation Systems Command Contract DAAJ01-73-C-0068, September 1974.

Adapted From Vertol Document D210-10888-1, Nov. 1974. Figura 2-15 Modified, With YUH-61A Added.

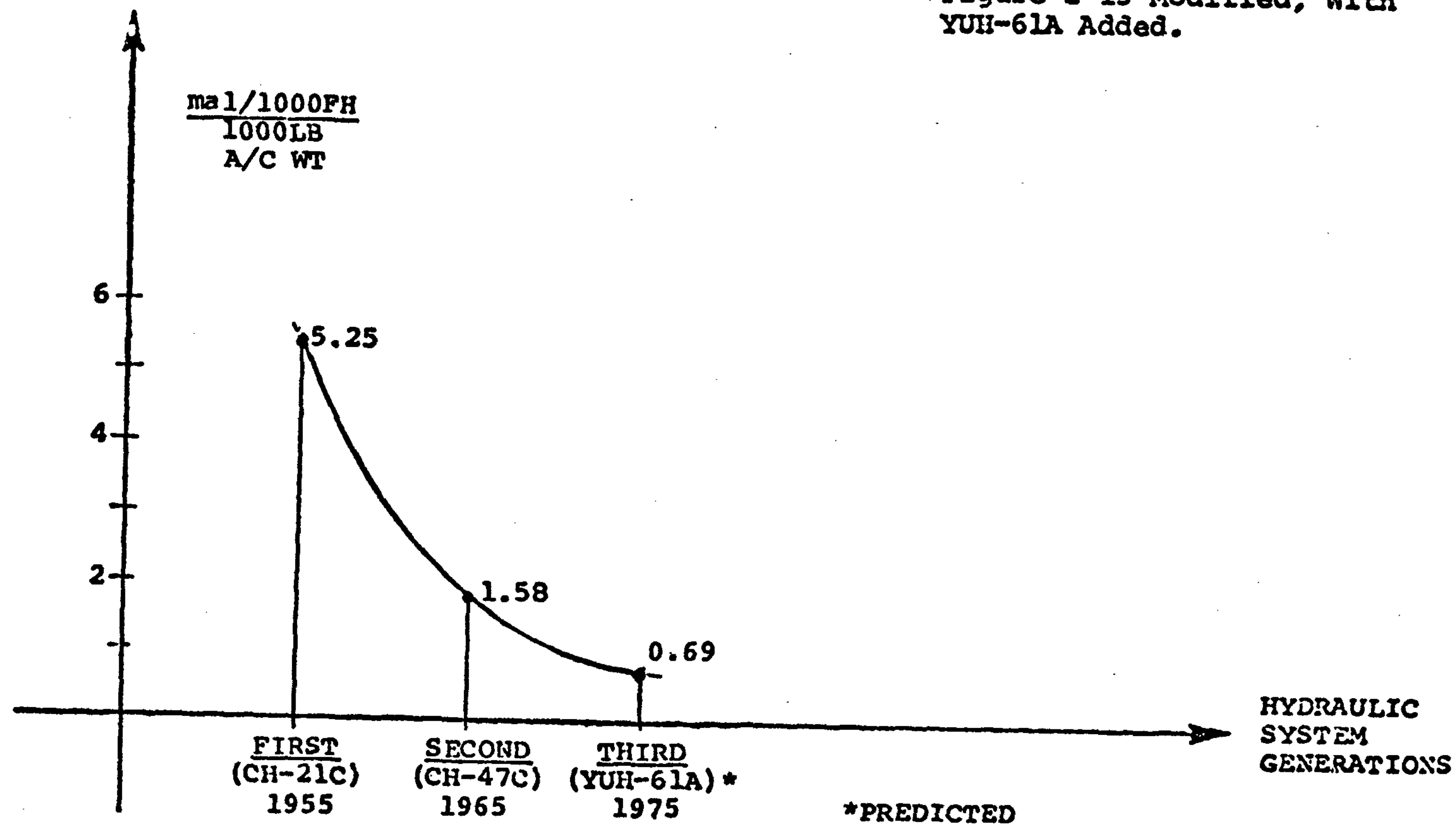


Figure 1. Typical Hydraulic System Reliability by Generation.

1. Flight control cylinders and irreversible valves ... leaking, internal failure, or loose.

2. Flight control cylinder ... loose or mission hardware, broken safety wires, or improper alignment.

3. Hydraulic lines ... leaking, loose, or worn.

The same study categorized five problem areas applicable to the larger CH-47C.

1. Flexible and rigid tubing, fittings, and clamps - chafed.

2. Flexible and rigid tubing and fittings - leaking.

3. Filters - out of adjustment, broken.

4. Servocylinder - excessive vibration.

5. Bulkhead fittings - loose.

The referenced report discusses each problem and notes which factor, or combination of factors, caused the problem. Figure 2 shows the proportional role played by each factor. Inadequate Technology and Specifications or Requirements together account for approximately 50% of the problems encountered by each helicopter. Operation and Maintenance accounts for about 10% in each case. This section will concentrate on the two categories that make up 50% of all system problems. However, some observations and recommendations concerning Design Execution and Test will be made. The maintainability state-of-the-art discussion will deal with Operation and Maintenance in more detail.

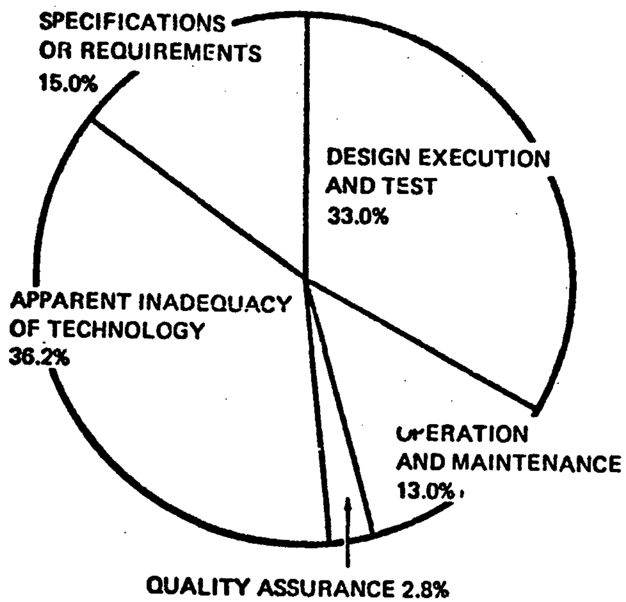
Specifications or Requirements

Specifications or Requirements are listed as a factor in all of the problem discussions. Most second-generation helicopters had no real reliability requirements. Weight and cost dominated the interests of design engineers and those responsible for procuring helicopters. Life-cycle cost was not a consideration. The latest U. S. Army helicopter procurement programs contain rigid controls of those elements that affect life-cycle cost.

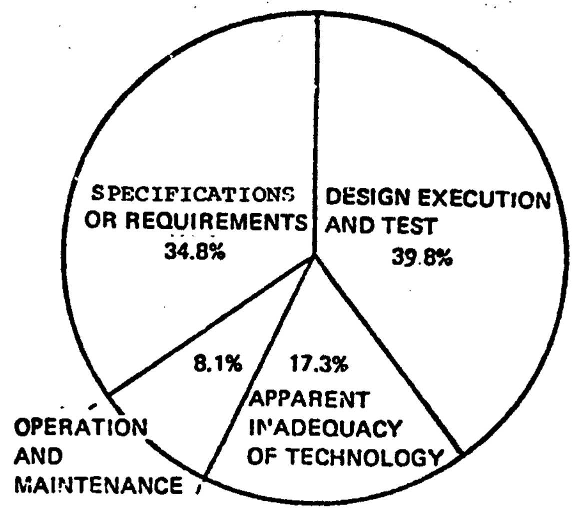
Inadequate Technology Areas

Table 1 lists five Inadequate Technology problem areas common to both the UH-1F and the CH-47C.

From Reference 1.



UH-1F



CH-47C

Figure 2. Hydraulic Subsystem Problem Causal Factors.

TABLE 1. RANKING OF CH-47 AND UH-1F HYDRAULIC SYSTEM INADEQUATE TECHNOLOGY PROBLEMS			
RANKING	INADEQUATE TECHNOLOGY AREA MENTIONED AS FACTOR	UH-1 PROBLEM NOS.	CH-47 PROBLEM NOS.
1	Helicopter vibration	2, 3	1, 2, 5
2	Bulkhead fitting design	3	1, 5
3	Hydraulic line fitting	3	2
4	Seal leakage - seal and filtration technology	1	4*
5	System pressure pulses	3	3

*Problem since reduced tue to product improvement action.

These five items apparently represent a good cross-section of the hydraulic system problems encountered by helicopter operators. During the UTTAS Program, the Government sent the airframe manufacturers a list of problems that impacted on the present fleet (Reference 2). The manufacturers were instructed to include design consideration (not to the exclusion of other problems) of the areas listed. The following problems were listed for the hydraulic subsystem:

1. Servo cylinders - Failures frequently occur in the form of leaks caused by shaft seal failure, resulting from contaminants (sand, dust, etc.) coming in contact with the seal - internal failure mainfested by chattering or a completely inoperative servo.

2. Irreversible valves - Moisture enters a valve because of inadequate seals, inducing chattering and jerking to cockpit controls with no pilot input.

[2]SYSTEM SPECIFICATION FOR UTILITY TACTICAL TRANSPORT AIRCRAFT SYSTEM, AERIAL VEHICLE DEMONSTRATION AND AIRWORTHINESS QUALIFICATION PROGRAM, AMC-SS-2222-10000B, Appendix II, 1 August 1975.

3. Hoses and lines - Chafing and leakage occurs at couplings.

4. Pump - Bearing failure and cavitation occurs, inducing chattering in servo cylinders and transmitting vibrations through the flight control system and airframe.

Helicopter Vibration

Helicopter vibration, while not normally considered a basic part of hydraulic system design, has a great impact on system reliability. Figure 3 illustrates the general differences between helicopter and fixed-wing aircraft vibrations.

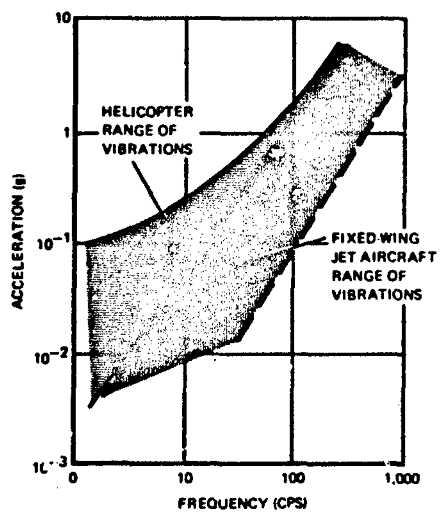


Figure 3. Generalized Comparison of Helicopter and Fixed-Wing Aircraft.

Rotor system vibration deteriorates the reliability of components in nearly every subsystem. One report correlated a 50% reduction in helicopter vibration to a 50% reduction in hose and tube failure rates (Reference 3). For these reasons, much

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[3] Veca, A. C., VIBRATION EFFECTS ON HELICOPTER RELAIBILITY AND MAINTAINABILITY, Sikorsky Aircraft Division, United Technologies Corp.; USAAMRDL Technical Report 73-11, Eustis Directorate, U.S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, April 1973, AD 766307.

effort is being directed toward vibration reduction. Examples are Bell Helicopter's Nodal System; Sikorsky Aircraft's Bifilar System; and Boeing Vertol's IRIS System. Due to these and similar attempts at reducing rotor system vibration, third-generation helicopters have reduced vibration level (g's) by approximately 67% as compared to those of the second generation.

However, helicopter vibration levels remain high, and hydraulic system design teams must provide for the effect of these higher vibrations.

Since one vibration-caused problem involves tubing and hoses that chafe adjacent lines and structure, an obvious solution is to route the lines through less congested areas. In practice, this is difficult to accomplish. Hydraulic line and electrical wire installations are regarded as very flexible and, therefore, are usually relegated to last priority when a helicopter design is being laid out. This is such an accepted practice that, very often, little thought is given to opposing it.

Bulkhead Fitting Design

Bulkhead fittings have a tendency to loosen and leak when subjected to rotor and hydraulic system vibrations. Reference 1 provides a detailed explanation of the problem and notes that a self-locking capability is required. Safety wire is not desirable, because: (1) fittings are often used in areas where access is poor and the task of safety wiring is usually difficult, and often nearly impossible; (2) the use of safety wire degrades maintainability because of the increased installation time required and the possibility of minor injury (scratches, punctures, etc.) to personnel. State-of-the-art locking devices could easily be adapted to the fittings in order to solve this problem.

Hydraulic Line Fitting Design

Table 1 shows that hydraulic line leakage is a major problem in second-generation systems. Military Standard (MS) fittings tend to wear and leak after repeated connections and disconnections, especially since mechanics tend to apply improper torques to the fittings. This basic problem is aggravated by helicopter and hydraulic system vibration. Third-generation helicopters attacked the problem two ways, by:

1. Using new fitting technology.

2. Reducing the number of fittings required by incorporating a degree of modularization.

Where possible, fittings may be completely eliminated by joining one tube directly to another via swaging, brazing, or welding. Swaging has the most desirable characteristics for use in U. S. Army helicopters because it is least susceptible to contamination during the joining process and no special mechanical skills are required.

U. S. Army helicopter operators may never be able to realize the full benefits of swaging because of the Army's peculiar operating and maintenance requirements. The Army must operate its helicopters in forward areas, sometimes under primitive combat conditions. Often, these requirements dictate that small numbers of helicopters operate at scattered sites. Under these conditions, the availability of swaging tools cannot always be guaranteed. Presently, mechanics can sometimes substitute a line from a nonessential system for a damaged line in a critical system in order to complete a mission or return to home base. They sometimes carry spare flexible hoses to use as semiuniversal substitutes for damaged lines. Therefore, under combat conditions, systems with swaged connections may not have the flexibility of those that employ threaded fittings.

Some third-generation, and all later Army helicopter hydraulic systems, will undoubtedly have a certain amount of swaged tubing because the concept promises so many benefits. However, its use must be on a selective basis.

Modularization provides direct and significant benefits to reliability and safety by reducing the number of fittings and leak points. Fewer fittings and connections also means that there are fewer points where contamination, both by air or particulate matter, can be introduced into the system.

The ultimate step in hydraulic system modularization is the Integrated Actuator Package (IAP), which is also referred to as a Modular Actuator Package (MAP). This concept combines power generation, control and actuation in a single package. The IAP will probably find its most effective use in random applications, such as when there is a need for an actuator in some part of the airframe that is remote from a hydraulic power source, or in large helicopters with widely separated hydraulic systems (Reference 4). In general applications, the IAP may not be competitive with conventional systems since excessive component duplication may result, and thereby degrade overall system reliability.

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[4]Murphey, R. C., and Pederson, N. F., MARKETING STUDY OF FUTURE AIRCRAFT HYDRAULIC REQUIREMENTS, Sperry-Vichers Division, Sperry Rand Corporation, May 1975.

Inadequate Seal Life

Disregarding problems that are peculiar to certain designs, there are two basic factors that affect seal leakage:

1. Seal and actuator bore technology and design experience.

2. Filtration technology.

Rotor feedback loads greatly influence control actuator seal reliability. Table 2 shows these loads for some Boeing-Vertol helicopters of various gross weights. The loads are aerodynamic and inertial, and after transmission through the swashplate, the per-blade-per-rev frequency content must be reacted by the actuators. Adequate actuator cylinder area and cylinder wall thickness are selected to provide the desired actuator stiffness. This stiffness is 10 x 10^4 pounds per inch (in trim flight position) for the CH-47 upper boost actuators. Despite this large design stiffness, the feedback loads cause cylinder

TABLE 2. FLIGHT CONTROL SWASHPLATE LOADS THAT ARE FED INTO ROTOR CONTROL ACTUATOR OUTPUT PISTONS

Helicopter Model	LOADS*			Actuator Stroke (in.)
	Steady (lb)	Alternating (±lb)	Frequency (Hz)	
BO-105	-364	40	28	3
YUH-61A (UTTAS)	-600	420	19	5.6
CH-47A	-1800	800	12	12
CH-47B/C	-500	2800	12	12

*3000 feet, Cruise Condition

axial deflections and thereby bore wear at the trim position. This condition is aggravated by the fact that the actuators may have a band of reduced stiffness around the null position due to internal leakage through the piston seal and in the control valve.

A newly installed CH-47 swashplate control actuator may deflect 0.025-in. double amplitude; with usage the deflection may build up to as much as 0.070-in. double amplitude. This is one cause for the relatively short lives of helicopter power control actuators. Operating a CH-47C actuator for

1200 flight hours would result in approximately 60 x 10^6 seal cycles. This number includes only 5 x 10^6 control system input cycles (pilot and SAS); the rest are alternating feedback load deflection cycles. Therefore, a proper endurance test of such an acutator would require applying 5 x 10^6 cycles to the input side (as required by MIL-F-9490), and at the same time, applying 55 x 10^6 cycles of rotor feedback loads to the actuator output rod (Reference 5).

Another serious problem related to seal life is the constant and comparatively large amount of small-particle contamination that is generated internally. There are two sources of particle generation. The first is the constant pressure fluctuation across the piston head. This causes every elastomeric seal (static or dynamic) to be slightly compressed and released at the rotor system load feedback frequency, and results in a slight but constant amount of O-ring wear. The size of the wear particles is generally very small (below 5 microns). These particles cause the often dark, or almost black, color of the hydraulic oil contained in a helicopter flight control hydraulic system. This type of contamination has not created any real problem and it has not been a known cause of any component malfunction.

The second source of particle contamination is the constant piston rod deflection cycles, which generate metal-to-metal and seal-to-metal wear particles. The particles are very small (less than 5 microns) and the materials may be of considerable hardness. As the density of the materials within the system increases, the effect may reach that of a very fine liquid honing or lapping compound. This state creates increased wear and contamination, presenting a self-destructive mechanism. Depending on its extent, control over the density of this small-particle contamination may be required.

An equally important factor in controlling this problem is the proper choice of materials for cylinder walls, piston rods, piston heads, glands, and the internal protective surface coatings for power control actuators. Under high-load, high-cycle conditions, aluminum cylinder housings with grey anodized bores generally do not provide much more than 350 hours Mean Time Between Failures (MTBF) of acutator life. The failure mode is, invariably, wear (removed metal) of the cylinder bore at the position of the piston head when the actuator is trimmed for forward flight. This cylinder bore wear will progressively

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[5] Krauss, H. G., LONG LIFE DYNAMIC SEALS FOR HYDRAULIC FLIGHT CONTROL ACTUATORS AND OTHER HIGH CYCLE RATE COMPONENTS, The Boeing Vertol Company, October 1971.

destroy the seal at the piston, thereby allowing ever-increasing amounts of load deflection to develop. Experience has shown that using a hard anodized aluminum cylinder bore may increase life (MTBF) of a helicopter power control actuator from two to four times over that of an actuator with a grey anodized bore; the actual improvement depends on the environment of the helicopter. Whenever rotor control loads are of a relatively large magnitude, the best actuator life can be obtained by using steel cylinder housings or steel sleeves in aluminum housings.

Seal Technology

Basic seal configurations have changed very little in the past 10 to 15 years. New materials have been developed, and these have provided increased durability. Additionally, there has been some optimization of dimensions for shaft and piston seals to reduce leakage, especially at lower pressures and temperatures. Seal manufacturers contacted were those major manufacturers considered to be actively pursuing new approaches. They were Parker, Shamban, Greene Tweed, 3M, and Precision Rubber. It probably would be accurate to say most seal manufacturers are directing the major portion of their attention toward optimizing existing configurations and materials that are in use today. The materials most often mentioned are polymide, mytrel, polymite, and of course improvements in teflon and nitride compounding. This optimization is primarily directed at providing seal life increases in specialized applications.

Efforts to develop seals with entirely new configurations and materials are proceeding at a lower intensity, and none promise to have any immediate impact on helicopter hydraulic system reliability. One interesting new concept, which may provide improved reliability, is the unvented seal discussed in Appendix C, however this seal remains to be rigorously evaluated.

There are two available seals that are currently considered most acceptable by Boeing Vertol for high-cycle helicopter flight control actuators. These are the Double-Delta II channel seals of Turcon* tetrafluoroethylene (TFE) manufactured by W. S. Shamban, and the G-T ring seal assemblies manufactured by and proprietary to Greene, Tweed and Company.

The Double-Delta II seals are similar to the Double-Delta seals made of Turcon TFE that Boeing Vertol has used on new design actuators for the past eight years (Figure 4). The older seals are used in standard O-ring grooves per MIL-P-5514F.

*Turcon is a specially processed virgin Teflon material proprietary to Shamban.

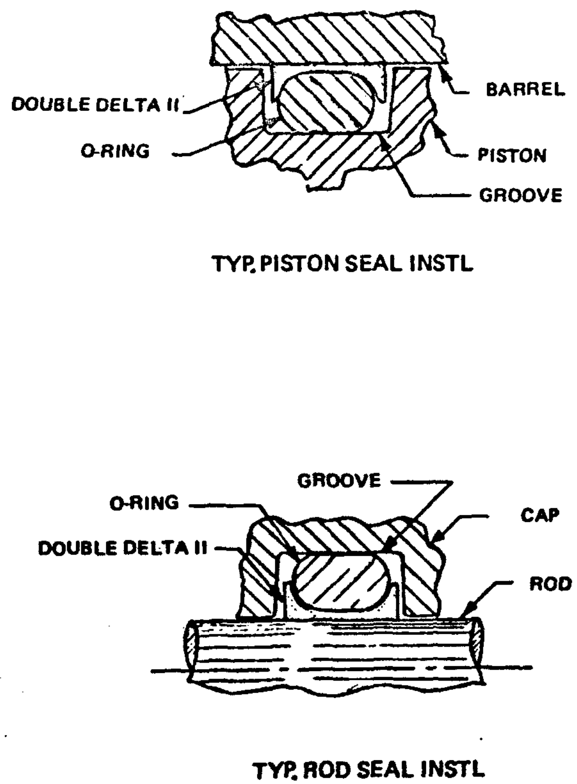

Figure 4. Typical Shamban Double-Delta II Seal Installation.

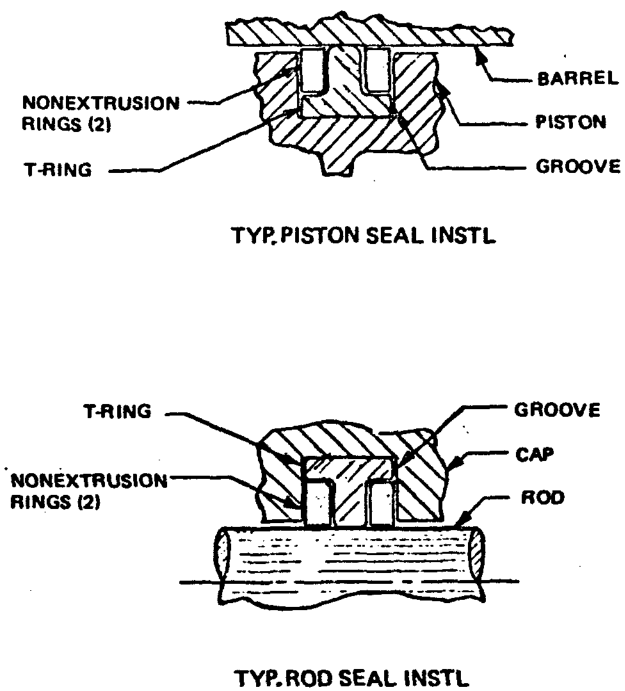

Figure 5. Typical Greene, Tweed G-T Seal Installation.

The new seals have some dimensional changes that provide improved low pressure leakage characteristics and longer seal life. Additionally, the new seals use a 5% molydisulfide-filled Turcon material known as Turcon 99. This material provides longer life in short-stroke dither-type cycling of actuators. The Turcon Double-Delta seals were extensively tested at Boeing Vertol and excellent results were obtained. A test of the Turcon Double-Delta II seal indicated a potential life of at least double that of virgin Teflon seals with the standard glyd ring configuration. A report of the test was presented to the SAE Committee A-6, Combined Meeting No. 71 of October 4-8, 1971 (Reference 5).

The typical G-T ring is shown in Figure 5. These consist of an elastomeric ring having a tee-shaped cross-section, and two nonextrusion rings of Teflon, installed in standard O-ring grooves per MIL-P-5514F. These rings were not included in the Boeing Vertol test mentioned above, but have since gained acceptance in helicopter control systems. The elastomeric tee ring is now nitrile-treated with fluorine gas, and the Teflon backup rings now include larger quantities of graphite than when the rings were first introduced. According to Greene, Tweed and Company, these changes have resulted in reduced friction and reduced heat generation, and ring life has been significantly increased. Bell Cobra helicopters now use G-T rings in upper boost actuators and the actuators are exhibiting good life characteristics. The rings were retrofitted to the Cobra in order to solve a known problem of severe wear on the hard anodized bore surfaces of aluminum cylinder barrels.

There has been recent emphasis on protecting fluid seals by the use of improved scraper rings and external dust boots. Scraper rings do not require maintenance attention, do not interfere with actuator maintenance, yet can provide adequate protection under most environmental conditions. Under severe environmental conditions, scraper seals are not completely adequate (Reference 6). Seal manufacturers are in the process of developing new scrapers for use under these conditions. One manufacturer, the Parker Seal Company is working with Dr. Fitch of Oklahoma State University to develop a new generation of scraper seals. Dr. Fitch is well known for his work in the area of hydraulics, particularly fluid contamination.

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[6] Huffner, J. L., and Dockswell, Sheldon, U. S. ARMY HELICOPTER HYDRAULIC SERVO CYLINDER RELIABILITY AND MAINTAINABILITY INVESTIGATION, USAAMRDL Technical Report 73-29, May 1973.

At present, boots are necessary in extremely severe environments. However, boots are not completely satisfactory because they often remain unattended after being worn out, and can serve as a trap for dust, sand, and rain (Reference 7). The long-term solution is to eliminate the requirement for boots by improving scraper seals. The more easily achievable short-term goal should be to identify and employ boot materials that are less susceptible to wear out, and to develop boot designs that do not invite mistreatment by mechanics.

Filtration Technology

Filtration technology improvements have increased system reliability during the preceding generations (Reference 1 and 8). The UH-1F helicopter is a prime example. It originally had 25 micronic (MIL-F-5504) filters, but contamination problems dictated increasing the filtration level to 15 microns (absolute). The system suffered from two major problems:

1. Initially, the designers did not fully appreciate the level of cleanliness the system servovalves required.

2. During service, the combination of internally-generated metal particles and routine external contamination maintained the particulate quantity at a level beyond the filter's capability (Reference 1).

Today, there is general debate as to what is an acceptable contamination level for air vehicle hydraulic systems. The SAE A-6 Committee, among others, is actively working on a program that hopefully will answer that question.

There is general consensus that a minimum of 15-micron (absolute) filtration is necessary. MIL-H-5440-F specifies 5 microns (absolute) for Navy aircraft and 15 (absolute) for Air Force and Army aircraft. The Navy is convinced that the finer level of filtration is necessary. In recent years the

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[7]Gillis, E., ARMY AIRCRAFT HYDRAULIC FLUID ANALYSIS PROGRAM, Directorate for Research Development and Engineering, SD&Q Technical Report 75-4, July 1975.

[8]Geier, W. C., and Potts, P. G., RELIABILITY AND MAINTAINABILITY ANALYSIS OF CH-53 AND CH-54 HELICOPTER SUBSYSTEM AND COMPONENTS, Sikorsky Aircraft Division, United Aircraft Corporation, Document SER-50865; U. S. Army Aviation Systems Command Contract DAAJ02-71-A-0303, January 1974.

Navy has successfully increased the MTBF of hydraulic system components by initiating a vigorous contamination control program. Component failures were decreased by 17% in A-6 and F-4 aircraft, with decreases as high as 60% in specific models (Reference 9).

The Navy program was not one of simply installing 5-micron (absolute) filters in their aircraft hydraulic systems. First, they adopted an existing SAE-industry standard for system contamination levels (See Table 3). They initially selected Class 5 of that standard as the maximum allowable contamination level for all model Navy aircraft, then began a program that encompassed 5-micron (absolute) filter retrofit, design requirement revisions, maintenance personnel orientation, technical manual revisions, and ground support equipment (GSE) changes. The GSE changes were extensive. Periodic fluid sampling was initiated. Navy agencies then: (Reference 9)

1. Insured that all GSE used in testing or servicing of hydraulic systems and components was equipped with 3-micron absolute filtration.

2. Retrofitted portable hydraulic test stands to provide for self-recirculation cleaning and fluid sample-taking.

3. Procured 1-, 3-, 10-, and 55-gallon fill service units, specifically designed to provide contaminant-free fluid for systems and component servicing.

4. Established maintenance policies that would insure that all GSE was maintained and operated in a manner consistent with good contamination control practice.

5. Procured additional filter element cleaning and testing equipment and insured adequate maintenance support of that equipment.

6. Developed a new, more comprehensive Military Specification describing 3-micron absolute high-pressure filter assemblies for GSE use.

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[9]Margolis, M. H., WORLD-WIDE NAVY PROGRAMS CONTROL AIRCRAFT CONTAMINATION, Hydraulics & Pneumatics, November 1973.

TABLE 3. NAVY STANDARD FOR PARTICULATE CONTAMINATION

MICRON SIZE RANGE	PARTICLE CONTAMINATION LEVEL - BY CLASS						
	ACCEPTABLE						UNACCEPTABLE
	0	1	2	3	4	5	6
5-10	2,700	4,600	9,700	24,000	32,000	87,000	123,000
10-25	670	1,340	2,680	5,360	10,700	21,400	42,000
25-50	93	210	380	780	1,510	3,130	6,500
50-100	16	28	56	110	225	430	1,000
Over 100	1	3	5	11	21	41	92
Total	3,480	6,181	12,821	30,261	44,456	112,001	177,592

Navy standard for contamination level for hydraulic systems in naval aircraft and GSE. Class of contaimination is based on the total number of particles in a 100-ml sample of hydraulic fluid removed from the system.

Having decided that finer filtration was required, the Navy's comprehensive plan was the correct method of attacking the problem. However, their thoroughness makes it difficult to isolate that part of the reliability improvement which can be attributed solely to improved on-board filtration.

The Army has initiated retrofit of 3-micron (absolute) filters on hydraulic ground carts, but they will not be likely to achieve the Navy's results in the areas of maintenance personnel orientation and the employment of special hydraulic fluid servicing units. The reason for this rests with the Army's field mobility requirements and maintenance environments. The typical Army helicopter operating unit, in order to remain mobile, can less afford to acquire extensive GSE that must be transported and maintained. Additionally, Army helicopters usually operate under more severe dust and sand conditions, and endure more primitive maintenance environments than Navy helicopters. This latter factor tends to reduce the employment of GSE even when it is available at the user level. Therefore, special attention must be directed to the capacity and filtration level of on-board filters in Army helicopters.

System Pressure Pulses

The last area of inadequate technology that will be discussed is system pressure pulses. It is ranked fifth on the list of reliability problems in Table 1. These pulses cause hydraulic line fatigue and chafing, and severe fitting overstresses (Reference 1). The pulses are usually generated two ways:

(1) pressure surges caused by the actuation of system components, and (2) pump "ripple". These pressure pulses are usually of such short duration that electronic measuring equipment is required to determine pulse amplitude and duration.

Paragraph 3.6.4.1 of MIL-H-5440G specifies that system pressure shall not exceed 135% of normal operating pressure and calls for the use of electronic measuring equipment, or the equivalent, to measure pulse amplitude. Early second-generation systems often were checked with conventional pressure gages. Therefore, problem-causing short-duration pulses went undetected.

Pump ripple is more difficult to cure. This is a cyclic pressure variation that is dependent to the greatest extent on pump piston speed and port timing. However, the hydraulic system in which the pump is installed also has a marked effect on pulse amplitude. This effect is so significant that at least one pump manufacturer will not guarantee pump ripple characteristics except when the pump is installed in the manufacturer's own test rig.

Paragraph 3.2.13 of MIL-P-19692C, the current hydraulic pump general specification, states pulsations, measured at a frequency equal to or higher than the pump drive shaft speed, shall not exceed ± 10% of rated discharge pressure when the pump is tested in a circuit that simulates the actual system in which the pump is to be installed. Paragraph 3.6.10.3 of MIL-H-5440G, the current hydraulic system specification, requires that pressure pulsations be measured initially on a system mock-up or simulator, and then on the first aircraft before flight. However, MIL-H-5440G does not stipulate any requirements for a simulator.

Simulators are excellent design tools but, since even minor system differences affect ripple amplitude, the measuring of pressure pulses in the actual aircraft system is the ultimate test. Therefore, one must look to MIL-H-5440G for guidelines concerning the maximum allowable pressure pulse amplitude. It leaves this determination to the designer, without providing any guidelines. Admittedly, the relationship between amplitude, frequency, and individual system response to variances in these two factors could be difficult to define, but this is all the more reason for presenting guidelines.

Paragraph 4.2.2 of MIL-H-5440G states that ground and flight tests shall be conducted in accordance with MIL-T-5522D. MIL-T-5522D concerns itself with pump ripple, but uses line and component vibration monitoring as the primary means of control. It requires that visual and instrument data be collected from lines and component installations to ascertain

the levels of acceleration forces induced in the hydraulic system by different modes of operation. MIL-T-5522D leaves the determination of acceptable ripple and vibration levels to the designer without providing any guidelines.

MIL-T-5522D treats pump ripple in a more comprehensive manner than MIL-F-5440G. Additionally, it refers to MIL-STD-810 for vibration requirements; in doing so, it appears to provide for the detection of line and component vibrations that are induced by helicopter drive transmissions, rotors, etc. as well as those vibrations originating from within the hydraulic system. But the thoroughness of MIL-T-5522D makes compliance with it very expensive, and there will exist the temptation to obtain deviations from its requirements in order to reduce program costs. In the long term, it may be more beneficial to have MIL-H-5440 and MIL-T-5522 specify a maximum allowable ripple. Whichever method of control is selected, care must be exercised to prevent making either specification overly restrictive. Perhaps ripple and vibration criteria could be presented as recommended allowables, much like recommended tube spacing data is presented in Paragraph 3.11.28.8 of MIL-H-5440G.

The work scope of this program does not allow further investigation to determine the optimum means of ensuring control over system pressure pulses. Additional work is required, perhaps by the SAE A-6 Committee. The committee should consider the following options during their investigation.

1. Revise MIL-H-5440G to provide guidelines for allowable pressure pulses.

2. Revise MIL-T-5522D to provide guidelines for allowable pressure pulses.

3. Revise MIL-P-19692 to establish specific requirements for system simulators.

HYDRAULIC SYSTEM MAINTAINABILITY

Introduction

The maintenance penalties of typical second-generation medium lift helicopter (MLH) hydraulic systems (utility and flight control but excluding the hydraulic portion of the stability augmentation systems (SAS) are shown below) (Reference 10).

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[10] Anderson, K. W., and Hunt, R. L., HELICOPTER FIELD EXPERIENCE SUMMARY COMPARISON HANDBOOK, The Boeing Vertol Company, Document D210-10344-1, June 1972.

The average MLH hydraulic system accounts for approximately 6% of the maintenance man-hours (MMH) required to support the entire aircraft. The flight control hydraulic system accounts for approximately 3% of the total aircraft MMHs. Figure 6 shows that preventive maintenance accounts for approximately 47% of hydraulic system MMH, while corrective maintenance makes up the remaining portion.

Aircraft	Hydraulic System Contribution to Total Aircraft (less SAS) MMH (%)
CH-47	5.8
CH-53	7.0
CH-54A	5.7

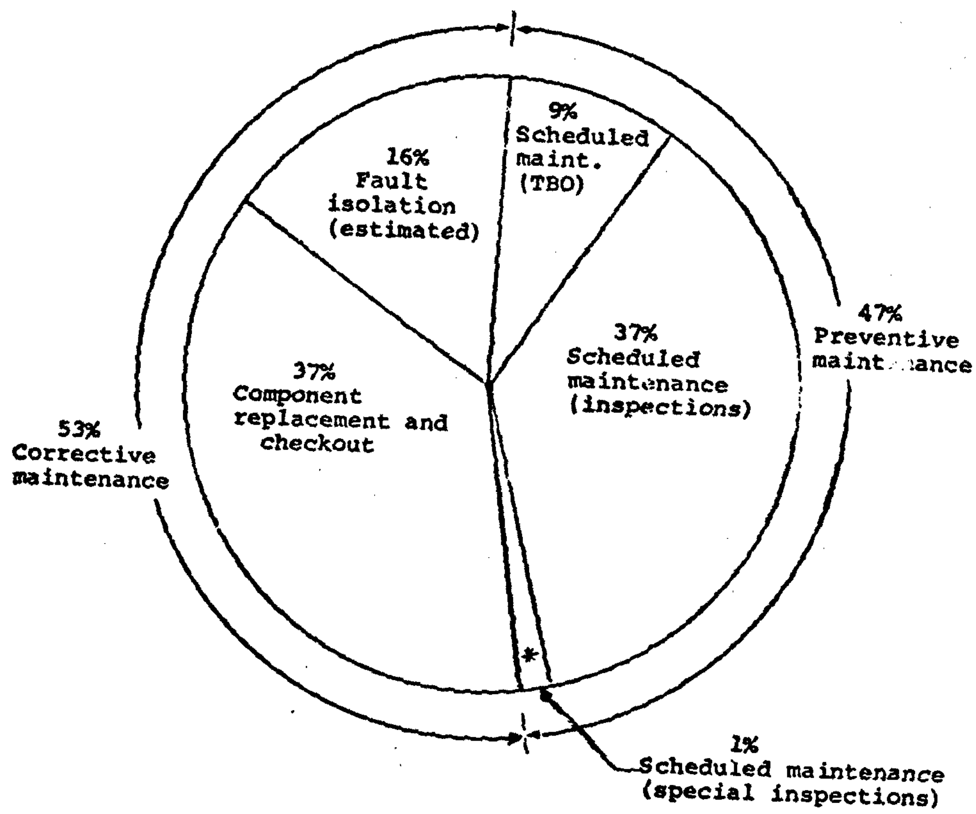
Preventive Maintenance

Inspection

The "overinspecting" of Army aircraft is a generally acknowledged problem. Present inspection frequencies often are not based on requirements that have been justified, but on early experience involving less reliable components. Army command personnel recognize the problem and are attempting to reduce its impact. An article in the U. S. Army Aviation Digest (Reference 11) explained the Army's efforts and expectations in this area, plus the preliminary results they observed. The basis for their efforts is a study the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory (USAAMRDL) initiated in March 1971 (Reference 12). From the study, specific scheduled maintenance schemes were developed for various aircraft. The basic principle involved is on-condition maintenance, i.e., to service only those components where deterioration and/or potential failures are detected by inspections. The project is called INSPECT,

[11] Cribbins, J. P., IF IT AIN'T BROKE-DON'T FIX IT, U. S. Army Aviation Digest, Volume 21, No. 7, July 1975.

[12] Wierenga, B. B., Blake, D. O., Hanson, R. E., and Cook, T. N., ANALYSIS OF ARMY HELICOPTER INSPECTION REQUIREMENTS, RCA/Government and Commercial Systems; USAARMDL Technical Report 72-35, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, September 1972, AD 754642.



Source: Data from Boeing-Vertol Document D34711001-1, undated. Table 2, CH-47A/B/C USAAVNTBD data. Fault isolation portion is estimated percent of total documented corrective MMH and is based on author's experience.

Figure 6. Second-Generation *MLH* (CH-47A/B/C) Preventive and Corrective MMH Ratios.

and it involves observing three helicopter companies (two UH-1, one CH-47) that are testing the new inspection system. Preliminary results indicated a 67% reduction in scheduled MMH for the UH-1 and a 45% reduction for the CH-47. Helicopter availability rates also showed significant improvement. Therefore, although overinspecting has been a problem in the past, the problem has been identified and corrective action is in progress.

Servicing

Servicing consumes a significant portion of preventive MMH. Third-generation helicopter hydraulic system servicing needs will change very little compared to the second generation. No radical sealing or concept improvements have been made and none are expected in the near future. But servicing is an area that has potential for maintainability improvement because the process of checking and replenishing fluid levels can be altered to substantially reduce total helicopter MMHs.

Second-generation systems typically have servicing points spread about the aircraft. As an example, the CH-47C has three hydraulic systems that require servicing. Two are serviced by climbing the helicopter to opposite sides of the aft pylon, while the third system is serviced in the aft cabin area. Some third-generation helicopters, including the proposed production version of the YUH-61A, use a single-point servicing system that, if applied to the CH-47C, could reduce servicing time by 25% and reduce total helicopter preventive MMH by nearly 15%.

The greatest responsibility for reducing preventive MMH expenditures rests with Army personnel who establish system requirements. A comprehensive logistics support plan, as provided by MIL-STD-1388-1, provides a means to attain specific preventive maintenance objectives. Systems can be designed that will go extended periods (perhaps 500 flight-hours) with only infrequent inspections by the flight crew. Servicing should be accomplished at ground level, from a central point. In those cases where central-point servicing is not possible or practical, simple ground rules should be established, based on actual Army field operating experience.

Corrective Maintenance

Corrective maintenance, which consumes the majority of hydraulic system MMH, has three major components:

1. Fault isolation.

2. Component replacement/repair.

3. System inspection and checkout.

Fault Isolation

For a relatively complex hydraulic system, fault isolation probably accounts for 25 to 50% of the total system corrective maintenance time. Troubleshooting is often a frustrating time for the average mechanic. Ultimately, he reverts to the "shotgun approach", whereby various components are replaced until the problem disappears. Effective hydraulic system fault isolation is hampered by:

1. The lack of adequate diagnostics.

2. Personnel skills versus design fault-isolation complexity.

Diagnostics

First-generation systems had only minimal diagnostic indicators. There were system pressure gages (or lights) for the pilot's use, and accumulator pressure gages that supplied preflight inspection information. The design considerations were primarily safety oriented, but since hydraulic systems were not complex and Army helicopter aviation was in its infancy, the meager amount of fault-isolation aids caused little concern.

Second-generation systems were more complicated; yet, there were almost no improvements in diagnostics. Some manufacturers incorporated quick-disconnect test ports for Peculiar Ground Support Equipment (PGSE), but generally, there remained only the system and accumulator pressure gages. The PGSE usually was not completely successful because it was not automated. It effectively reduced fault isolation time only when used by unusually competent mechanics; the various gages and meters required analytical processes beyond the average mechanic's capability.

Third-generation systems incorporate system pressure and temperature gages or lights plus reservoir low-level warning indicators. None of these are intended primarily as troubleshooting aids, and only the exceptional mechanic will use them as such. Most third-generation systems do have pump case drain-flow indicators. These are excellent diagnostic tools that warn of impending failure and assist

in fault isolation. Case drain-temperature indicators are available to complement the flow indicators, but it is doubtful that both are necessary.

The Grumman Aircraft Company is presently engaged in studies of diagnostics for aircraft hydraulic systems. There are tentative plans to install and test advanced diagnostics in a system simulator and then fly the equipment on two Navy fixed-wing aircraft. The planned testing will include a maximum system leakage flow indicator, part number AP-453-1, that Aircraft Porous Media, Inc., has had under development. The device can be installed in the return lines of hydraulic actuators to detect unusually high quiescent flow, yet ignore flow increases that result from normal actuator excursions. The developed unit is expected to weigh approximately ½ lb and be priced comparably to a pressure regulator valve. Once fully developed, this indicator would provide benefits similar to those offered by pump case drain flow indicators. Troubleshooting time would be reduced, and actuator seal deterioration would be detected early, allowing corrective action to be scheduled while the aircraft is grounded for other maintenance. Benefits would also be realized in increased mission availability and aircraft safety.

Justification of onboard diagnostic equipment on the basis of life-cycle costs is difficult. Diagnostics reduce troubleshooting time rather than "wrench-turning" time; therefore, MMH savings cannot always be clearly identified. In those instances when diagnostics are included in the original design, it becomes a prime target for cost-reduction efforts as the manufacturer struggles to produce the lightest and lowest cost helicopter.

With the growing trend toward more modularized components and integrated actuators, diagnostics will become important tools in the prevention of costly erroneous module removals. One Boeing-Vertol study indicated that high-cost hydraulic components have a 20% erroneous removal rate (Reference 13). This probably represents just a portion of the actual erroneous component removals. The

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[13] Sramek, J., Jr., ENGINEERING SERVICES TO DESIGN AND DEVELOP THE MOST EFFECTIVE APPLICATION OF A CONDITION MONITORING SUBSYSTEM FOR UTTAS ON A LIFE CYCLE BASIS, The Boeing Vertol Company; U. S. Army Aviation Systems Command Contract DAAJ01-75-C-0494(P6C), 31 July 1976.

discarded items usually are not accounted for, and neither are the units that should have been returned for repair but never reentered the supply system. Many items, such as check valves and solenoid valves, are discarded even though their replacement failed to eliminate the discrepancy.

Other sources have indicated that, for certain systems, a minimum of 50% of the component removals may be erroneous. A 1975 USAAMRDL report noted that 50% of Army aircraft maintenance diagnoses at the Organizational Maintenance Level were reported as being incorrect (Reference 14). One controlled experiment (not related to the USAAMRDL report), involving 13 experienced MLH mechanics, resulted in an average of 2.44 components replaced for each single component failure. The test involved 39 troubleshooting events on an installed auxiliary power unit (APU). The APU was selected because it included electrical, hydraulic, and mechanical components. The average mechanic in the study had a total of 11 years experience in aviation with 4 of those years on the MLH model used in the experiment.

Assuming it cannot be proven that developing diagnostics for hydraulic systems is cost-effective, the logical approach is to use diagnostics that were originally developed for other applications. Two interesting concepts are debris monitoring and high-frequency vibration analysis. Debris monitoring techniques vary, and include the monitoring of buildup rate as well as total accumulation. There have been several successful test programs that involved predicting hydraulic pump failures by vibration monitoring. One Boeing-Seattle report indicates that vibration monitoring was successfully used to detect both pump cavitation and reduced output (Reference 15). Development of these sophisticated units probably could be justified for drive transmission systems that are expensive, safety-critical, and nonredundant. Once the units are developed and costs have been reduced, some application to hydraulic systems may be realistic. The most likely candidate would probably be an automated vibration

[14] Holbert, C., and Newport, G., HELICOPTER MAINTENANCE EFFECTIVENESS ANALYSIS, Sikorsky Aircraft Division, United Technologies Corp.; USAAMRDL Technical Report 75-14, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, May 1975, AD A012225.

[15] THE DETECTION OF INCIPIENT FAILURE IN CERTAIN HYDRAULIC COMPONENTS, The Boeing Company, Seattle, Washington, Document A69-36018, 7 July 1969.

monitor, developed as an item of GSE. It would not add weight and cost to the aircraft system, and would be capable of determining the health of valves and actuators as well as pumps (Reference 13).

Personnel Skills and System Complexity

This problem stems from a number of factors, but the most important is probably high personnel turnover rates, including turnover at the operating unit level. This makes training and the acquisition of skills very difficult. As a result of these factors, the average Army mechanic learns by observing or performing repetitious tasks on a particular system rather than through acquiring basic knowledge that will serve him for all hydraulic systems. This is particularly true in the case of fault-isolation skills. The process of knowledge through repetition fails when:

1. The same problem occurs only infrequently.

2. An unfamiliar failure mode is encountered.

3. The mechanic must work on an unfamiliar system.

There is another serious fault associated with this process. Incorrect fault-isolation procedures, in particular that of replacing random components in the hope that the fault will be corrected, are very often transmitted to the new mechanic. The solution to this problem rests with diagnostic fault-isolation systems that do not require mechanics to interpolate, calculate, or draw conclusions. The logical concept is one where the mechanic is required to replace a specific component whenever he sees an extended button or the deflection of a needle. The Army obviously recognizes this problem; the UTTAS specification suggested the elimination of all interpretive work on the part of maintenance and flight personnel as a design target. As an example, the Boeing-Vertol UTTAS candidate helicopter (YUH-61A) has a flight control hydraulic system with only three modules:

1. Pump/cooler.

2. Supply/control with replaceable sensors.

3. SCAS/rotor control actuator.

The pump/cooler module has pump case drain (delta-pressure) flow indicators plus contamination indicators. The supply/control module has standard filter delta-pressure indicators plus pressure, temperature, and fluid level indicators. The pump/cooler delta-pressure and system temperature indicators provide the basis for on-aircraft troubleshooting. Many

actuator problems are readily identifiable; therefore, fault identification usually involves either the pump/cooler or the supply/control module. If system temperature is elevated (not due to blockage of the cooler core) or the pump case drain diagnostic buttons are extended, the pump/cooler module is replaced. Otherwise, the supply/control module is replaced. The mechanic still must be skilled enough to identify actuator and indicating system problems, so detailed fault isolation procedures were provided with the aircraft. Figure 7 provides an example of the logic charts that are a part of the procedures. The YUH-61A concept is a step in the right direction.

Component Replacement and Repair

The U.S. Army, recognizing the problems associated with the growing complexity of its systems, instituted the "Maintenance Support Positive" (MSP) Program (Reference 16). The MSP concept stresses the need for quick, easy identification of discrepant components and their speedy replacement. This concept eliminates many on-aircraft repairs and usually dictates at least some form of modularization.

There are a number of ways to speed replacement times and reduce MMH. One method is to eliminate the use of Military Standard type fittings where practical and employ new fitting concepts that promise to reduce maintenance time directly by eliminating work steps, and indirectly by increasing reliability. One example of this is a fitting made by Rosan, Inc. of Newport Beach, California. It requires a special boss and comes with MS 33656 flared tube connections (Rosan No. RF9800-13); MS 33514 flareless tube connections (Rosan No. RF9900-13); "Dynatube" tube connections (Rosan No. RF5000-13); and an end that allows welding to tubing (Rosan No. RF7700). The Rosan fittings are generally more expensive than the common MS fittings; however, as they gain field acceptance, the price difference should be reduced.

The fittings have these basic advantages:

1. Double sealing - an elastomeric O-ring is backed up by a metal-to-metal seal.

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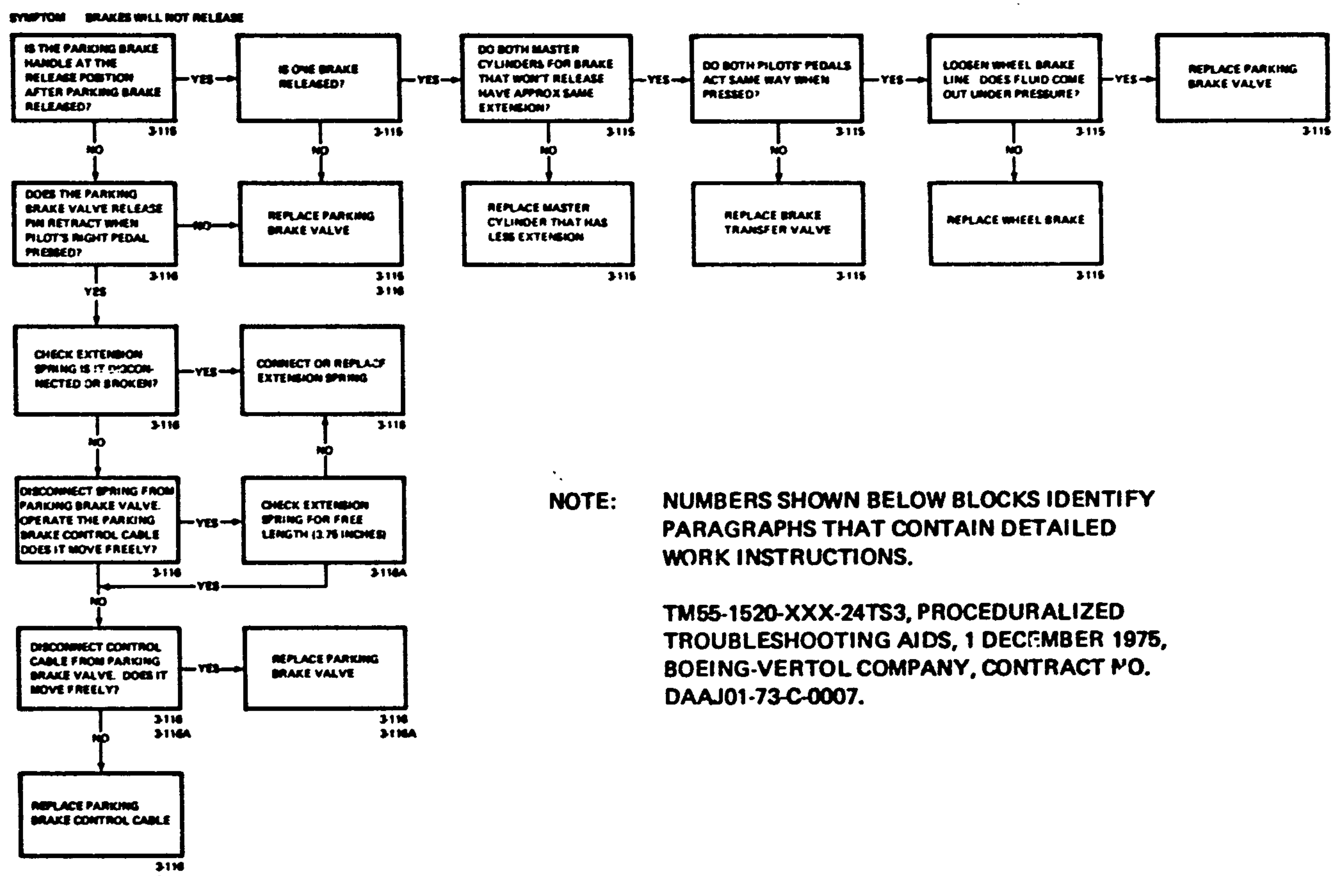
[16] MAINTENANCE OF SUPPLIES AND EQUIPMENT - MAINTENANCE SUPPORT POSITIVE (MS+) ARMY MAINTENANCE FOR THE SEVENTIES, Headquarters, Department of the Army, Washington, D. C., Circular No. 750-38, November 1971.



NOTE: NUMBERS SHOWN BELOW BLOCKS IDENTIFY PARAGRAPHS THAT CONTAIN DETAILED WORK INSTRUCTIONS.

TM55-1520-XXX-24TS3, PROCEDURALIZED TROUBLESHOOTING AIDS, 1 DECEMBER 1975, BOEING-VERTOL COMPANY, CONTRACT NO. DAAJ01-73-C-0007.

Figure 7. Fault Isolation Logic Chart

2. The fittings are torque-locked to the boss. No lock wiring is required, and the tube connections can be broken or made up with only one wrench, which is used on the "B" nut.

3. Significant weight reduction - the fittings weigh from 60 to 73% less than the MS 21902 union they replace, depending on the tube dash number size.

4. Lower profile - the fittings have a low profile compared to the standard MS 21903 union.

5. Replaceable - the fitting is replaceable in its boss using simple hand-operated tools.

The Rosan fitting is a two-piece assembly consisting of the basic boss fitting that has a row of longitudinal serrations, and a locking collar with internal serrations that mate with those on the fitting. The locking collar has external longitudinal serrations that mate with serrations in a recess in the boss. When the fitting is installed and the lock ring driven into the boss recess, the fitting is thoroughly torque-locked in the boss material, exhibiting minimum shear strength of 26,000 psi or more.

In addition to simplifying the basic tasks of changing a component, the Rosan unit eliminates the need for mechanics handling O-rings and reduces the requirement for stocking those rings in supply. Another significant advantage is that it eliminates the maintenance damage that often results when mechanics fail to react torque as they install or remove MS fittings.

One of the simplest methods of improving maintainability (plus reducing cost and weight) is often overlooked. More because of tradition than anything else, many small hydraulic components have been attached to structures by four fasteners. In most instances that number could be reduced to three or even two without any reliability or safety consequences. The YUH-61A was designed to meet more stringent crash load requirements than nearly any helicopters built in the past. Figure 8 shows the load limits imposed on the design. Yet, in reviewing off-the-shelf hydraulic component mount provisions, it was observed that the structural integrity of many units far exceeded the new, higher load limits. Further observation revealed that new components, then under design, were being laid out with an excessive number of mount bolts. In many cases, it was possible to reduce the number of mount bolts, thereby improving maintainability and reducing cost and weight.

ULTIMATE CRASH LOAD FACTORS

ULTIMATE CRASH LOAD FACTORS	N_x	N_y	N_z
APPLIED SEPARATELY	20 0 0 0	0 ±18 0 0	0 0 20 -10
COMBINED CONDITIONS	±20 ∓10 ∓10	± 9 ∓ 9 ∓18	+10/-5 +20/-10 +10/-5

Positive directions of load factors are shown below:

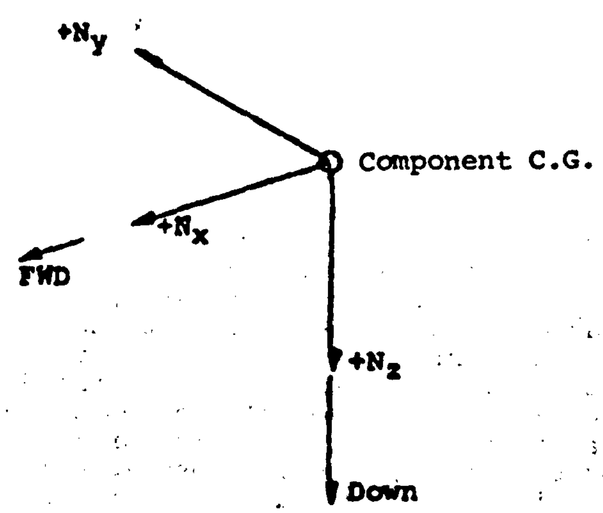


Figure 8. YUH-61A Component Ultimate Crash Load Factors.

Aircraft Inspection and Checkout

The inspection of hydraulic system repair work is a fairly rigid process. Other than the usual attempt to design a noncomplex part that allows early and easy detection of discrepancies, there is little the design team can add. But, system checkout after repair does offer opportunities to improve maintainability. System rig and operational checks can be simplified and need not rely on test equipment or the insertion of rig pins. For example, tolerances should be such that rig checks do not have to be made after an actuator is replaced. If a check is necessary, no more than a visual inspection of alignment marks should be required.

Conclusions

What steps can designers of the next generation of hydraulic systems take to alleviate the maintainability problems just discussed? Eight areas of improvement appear obvious:

1. Use a comprehensive logistics support plan as a major design program element.
2. Ensure that multi-system helicopters have ground-level single-point hydraulic servicing provisions.
3. Provide integral ground operation and checkout capability for all hydraulic systems.
4. Design some degree of modularization into the systems.
5. Survey diagnostics used in other systems for possible adaptation to hydraulic systems.
6. Develop simple, low-cost, GO/NO-GO diagnostics to reduce fault isolation time.
7. Use new line fittings that are not susceptible to mechanic's error or handling damage, and provide adequate wrench clearance at fitting locations.
8. Use only the minimum number of mount fasteners required and position them so all are accessible to maintenance personnel using socket and ratchets.

The eight improvements listed above are achievable via present technology, using off-the-shelf components.

HYDRAULIC SYSTEM SAFETY

Introduction

Hydraulic system safety problems are not peculiar to helicopters; military jet aircraft also require hydraulically boosted flight-control systems. However, the helicopter does pose a much more serious egress problem. A complete loss of control boost usually leaves the fixed-wing jet aircrew with the option to exit the aircraft, but a similar occurrence in a helicopter leaves the aircrew few, if any, options.

Major Accidents

The complete loss of hydraulic boost has not been a major problem with helicopters. The CH-47 has had four recorded instances of dual boost systems loss in 1,302,355 flight hours. Three of those four instances were the result of line leakage and one was caused by dual hydraulic pump failure. In most cases, loss of control occurred on or near the ground. Only one accident involved a loss of life; it resulted when the pilot elected to continue flight to his home field on a single hydraulic system after having experienced a line failure. Subsequent to overflying a major USAF base, a second hydraulic line failure occurred, and the pilot alone was killed in the resulting crash. Table 4 lists CH-47 dual hydraulic failures. The third-generation fail-operational system feature is expected to eliminate hydraulic control boost disablement as a cause of accidents.

Although not a direct part of the hydraulic design discipline, hardware must be considered when a hydraulic actuator is installed in a flight control system. In 1,302,355 flight-hours of CH-47A and B operation, there were at least eight catastrophic accidents that resulted from improperly installed flight control system bolts. Of these, three were identified as swashplate control actuator-oriented. MS 27576 impedance bolts have since become available, and are now used in critical control joints. No control disconnect incidents have occurred since the new bolts were installed. The YUH-61A utilizes a dual (redundant) mechanical control system up to the control actuator, and therefore does not require impedance bolts. However, BACB30ST (Boeing-Vertol P/N) self-retaining bolts, which contain pawls to prevent backout, are used at the two (upper and lower) actuator connection points because redundancy does not exist there. Impedance and self-retaining bolts are heavier, more expensive, and degrade maintainability. But the anticipated savings in lives and equipment should more than make up for those drawbacks.

TABLE 4. RECORDED CH-47 DUAL HYDRAULIC FAILURES			
Items	A/C Destruction	Loss of Life	Failure Cause
Lines	Yes	Yes	Line joints leaked*
Lines	Yes	No	Crossed lines
Lines	Yes	No	Unknown
Pumps (2)	No	No	Internal Failure

* Pilot elected to continue flight after loss of first system
NOTE: Based on 1,302,355 FH

USAAAVS Data

Precautionary Landings

A very significant hydraulic system safety problem is the precautionary landings that occur each year from hydraulic system leakage. Pilots will often go into an emergency descent upon the loss of one boost system. A leaking hose spraying into a cabin or cockput area makes it likely that descent will be even more hurried. Table 5 shows CH-46 and CH-47 precautionary landings that were caused by hydraulic systems. For each helicopter, tubes, hoses, and fittings account for more than 50% of the landings. Even smaller, single-rotor helicopters with relatively short line runs have similar problems with precautionary landings. The following is a quote from the thirteenth U. S. Army Agency for Aviation Safety (USAAAVS) Weekly Summary, 20 November 1970:

> "Hydraulic failures in the UH-1 and AH-1G continue to plague us. Of 933 mishaps attributed to material malfunction/failure and inadequate maintenance in the last six months, 351 were hydraulic problems. Experience indicates the majority of these occur in hoses and lines."

While fail-operational systems may tend to alleviate the sense of emergency felt by some pilots during leakage-caused precautionary landings, there appears to be very little doubt that, even with fail-operational systems, pilots will execute hurried precautionary landings in certain situations. Table 6 shows that nearly 30% of the mishaps caused by CH-46 and

TABLE 5. MATERIAL-CAUSED HYDRAULIC BOOST PRECAUTIONARY LANDINGS, 1967-1970

Component	CH-46	%	Rate	CH-47	%	Rate
Actuator	3	2.80	.59	4	3.45	.47
Tube Assembly	19	17.76	3.72	29	25.00	3.40
Hose Assembly	37	34.58	7.25	25	21.55	2.93
Fitting	12	11.21	2.35	8	6.90	.94
Seal	1	.93	.20	3	2.59	.35
Pump	13	12.15	2.55	20	17.24	2.34
Pump Drive Shaft Diseng.	0	0	0	9	7.76	1.05
Cooler	4	3.74	.78	4	3.45	.47
Valve End Cap	9	8.41	1.76	0	0	0
Miscellaneous	6	5.61	1.18	9	7.76	1.05
Unknown Leak	3	2.80	.59	5	4.31	.59
Total	107	100.00	20.96	116	100.00	13.58

CH-46, A and D Models, 510,577FH, Navy Safety Center Data
CH-47, A, B, and C Models, 853,905FH, USAAAVS Data

TABLE 6. HYDRAULIC SYSTEM MISHAPS, 1961-1970

Hydraulic Malfunction	CH-46	CH-47
Single Flight Boost Loss Resulting in P/L	131	92
Single Flight Boost Loss Resulting in Accident	1 (1)	
False Boost Pressure Loss Indication/Fluctuation		19
Leakage of Hydraulic Fluid (Flt. Boost not Lost)	56 29%	40 27%
Dual Flight Boost Loss During Landing	1	2
Dual Flight Boost Loss Resulting in Accident		2 (2)
Miscellaneous	4	1 (1)
Total Mishaps (Major Accidents)	193 (1)	156 (3)

CH-46, A and D Models, 581,110FH, Navy Safety Center Data
CH-47, A, B, and C Models, 962,305FH, USAAAVS Data

CH-47 hydraulic systems did not involve a complete loss of boost. A majority of these can be attributed to the utility hydraulic system rather than the flight hydraulic system. Since third-generation systems do not have high-pressure hydraulic lines in the cabin/cockpit area, this may prove to be less of a problem. Still, future systems should be designed for use with high flash point fluids, and lines should be located so leakage will not result in fluid spray on hot engines, pneumatic lines, etc. Full use should be made of new fitting and swaging technology to reduce potential hydraulic system leakage.

HYDRAULIC SYSTEM VULNERABILITY

Introduction

It is easy to cause critical damage to a hydraulic system. Almost any hit can and does result in loss of the basic element (the fluid) that is required for the system to function. The impact of this loss on the continued operational capability of the aircraft depends entirely on the function of the system affected. Table 7 gives a criticality analysis of various types of helicopter hydraulic systems when subjected to ballistic impact.

Traditional single-shot kill analyses comparing first- and second-generation systems show that second-generation systems would be twice as likely to be hit (with resultant mission aborts) than first-generation systems. This is because all elements are repeated in a dual system and therefore the projected areas are doubled. In the field, second-generation systems proved to be even more vulnerable than the single-shot analysis indicated. Multihit encounters were common, and effective system separation was often poor. With second-generation systems, the result of a second open was catastrophic.

Third-generation systems essentially are designed to be safe after two opens. They have been designed with effective system separation to achieve true ballistic redundancy and have made some use of modularization to obtain minimum system area.

Hydraulic Fluid Flammability

There are current military-directed programs that have the objective of replacing MIL-H-5606 with a "nonflammable" or high flash point fluid. Army programs are specifying MIL-H-83282 Fire Resistant Fluid. Tests with this fluid by Ballistics Research Laboratory (Memo Report No. 2246) and by others indicate that use of the fluid will result in systems with reduced fire potential. Combat experience with MIL-H-5606 is summarized

TABLE 7. CONSEQUENCES OF BALLISTIC IMPACT ON VARIOUS HELICOPTER HYDRAULIC SYSTEMS

GENERATION	TYPE SYSTEM	A/C USING	CONSEQUENCE OF SINGLE OPEN	CONSEQUENCE OF TWO OPENS (HYD ONLY)
1st	Single Flight-Control Boost, Manual Reversion	CH-21 UH-1 A/B	Mission Abort	NA
2d	Dual Boost, No Manual Reversion	CH-46 CH-47 CH-53 CH-54	Mission Abort	Attrition
	Mission Critical Utility Hyd System-Powered Elements	CH-46 CH-47 CH-53 CH-54	Mission Abort	NA
3d	Multi-Boost System With First-Fail Operational Capability	YUH-61A XCH-62A	Continued Mission Completion Capability	Mission Abort

in Table 8 for CH-46/CH-47 and UH-1 aircraft. This particular data might indicate that fire probability is related to system pressure; however, conclusive proof of this relationship does not exist. The methodology established by BRL to assess the fire potential of hydraulic systems due to ballistic impact uses line spacing from aircraft skin and projectile impacting velocity as the only variables. System pressure is not considered to be an affecting variable.

Vulnerability Design Options

Providing ballistic protection for an existing system quickly and at low cost has been a relatively uncomplicated procedure. The usual approach has been to protect critical areas with armor. The degree of protection provided using this approach depends on what penalties are considered to be acceptable in the area of cost, weight, and maintainability. A new hydraulic system design permits the design team various options as to the method of attaining a specific degree of protection.

Reducing the ballistic vulnerability of helicopter flight control hydraulic systems can be achieved by the following methods:

1. Reducing hit probability by:
   a. Adding armor or shielding.
   b. Reducing component size.
2. Reducing kill probability by:
   a. Providing system redundancy.
   b. Providing a ballistically tolerant design.

Armor

The common approach to ballistic vulnerability of critical flight control components, such as the upper boost actuator, has been the use of local armor, external to the component. External armor is advantageous from the standpoint of cost and simplicity of design and fabrication. This is especially true in the case of adding protection to existing designs. However, there exists a significant weight and envelope penalty, and once the armor is in place, there is added difficulty in access and maintenance of the actuators. In addition, full protection is difficult to achieve due to limited space availability and structural support limitations.

TABLE 8. FIRE CAUSAL FACTORS - COMBAT HYDRAULIC DAMAGE

	UH-1*	CH-46	CH-47
TOTAL HITS IN PERIOD	2967	4154	2937
Hydraulic System Hits	61	104	94
Hydraulic Fires	0	7	4**
Fires/Total Hits	0	.00168	.00136
Fires/Hyd System Hit	0	.068	.043
System Pressure	1000	3000	3000

*Army Material Systems Analysis Agency Technical Memo No. 46, 1969; Analysis of Combat Damage in U. S. Army UH-1 Helicopters in Vietman

**Falcon Research Report (unpublished, to be Ballistics Research Laboratory Technical Report)

Another method of providing armor protection for the actuator is to attach the armor directly to the actuator assembly; the plating can be made to fit the contours of the actuator. The result is greater ease in accessibility and maintenance of the unit, plus reduced weight compared to the flat plate armor. Reference 17 describes the progress being made in the manufacture of specially shaped armor components.

The third method is to actually manufacture portions of the component using armor materials. For example, barrels could be made of extruded dual hardness steel (DHS) tubing. Some caution is to be exercised when considering this type of integral armor construction, since the fatigue properties of DHS as a structural material have not yet been fully investigated, nor has its suitability as a long-life dynamic surface material. Integral armor construction in cylinders and valve housings presents the possibility that dents caused by ballistic impact could result in the binding of internal parts, such as pistons and valve spools.

Shielding

The technique of shielding critical hydraulic system components using heavy aircraft structures or other components is relatively ineffective. The principal limiting factors are:

1. Very few helicopter components can withstand ballistic projectiles.
2. Critical hydraulic components usually are located throughout the helicopter.

The grouping of hydraulic system components into modules, especially when mounted in heavy transmission elements, could provide some protection via shielding. However, it is not feasible to expect long hydraulic line runs to be located so as to obtain shielding over any significant length.

Size Reduction

Hydraulic actuators are unique among critical aircraft components, in that reducing the size of an actuator can be effective in reducing its overall vulnerability. Normally, when an aircraft component is reduced in size, the reduction in presented

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[17] Sliney, J. L., MANUFACTURING TECHNOLOGY - DUAL PROPERTY STEEL ARMOR FOR AIRCRAFT COMPONENTS, Nuclear Metals Division, Whittakes Corp., USAAVLABS Technical Report 69-15, U. S. Army Aviation Materiel Laboratories, Fort Eustis, Va., April 1969, AD 854769.

area is more than offset by its increased kill probability if hit. For a hydraulically powered actuator, the kill probability when hit is always high due to the large percentage of its area that is critical. Offsetting this is the fact that it can be very difficult to design anti-jam features into small actuators.

Redundancy

Ballistic redundancy requires total duplication of load paths, power supplies and control elements. Second-generation upper boost actuators are redundant only to the extent that dual pistons, supplied by separate hydraulic systems, are used. Control input, power output, and to some extent, single structural load paths, exist. Structural load path redundancy can be designed into actuators by use of split housings, so that ballistically induced cracks cannot spread from a damaged system to one that is undamaged. Most third-generation systems have dual control input and dual power output.

Second- and third-generation power distribution systems are usually functionally redundant. Functional redundancy, however, does not guarantee ballistic redundancy if the system installation is deficient. Location of system line runs in close proximity can result in a significant probability of losing both systems due to a single hit. It should be noted that a probability of killing multiple systems due to a single hit will always exist, and can only be realistically controlled by making a maximum effort to reduce system complexity.

Ballistic-Tolerant Design

Ballistic tolerance requires a component to function after sustaining a ballistic impact. All modes of failure, such as opens, jams, and loss of boost, must be accounted for in the design. Second-generation rotor control actuators are functionally redundant, in that dual operating pistons, with separate power supplies, are used to provide an output signal to the rotating swashplate. However, these actuators are not ballistically redundant, in that a single hit can result in the loss of both outputs. This is due to the fact that hits on one hydraulic piston may result in a jam condition that the undamage piston cannot overcome.

One approach shown to be viable through the third-generation YUH-61A design and test program is to ensure that redundant structural load paths exist so that ballistic impacts do not result in an open, and to design the actuator so it is self-clearing for jams. A dual boost system can be designed to clear jams if the undamaged system has sufficient reserve

capability to simultaneously clear the jam and react flight loads. The key to this concept is the detail design of the power cylinder portion to ensure that the required clearing forces are as low as possible.

Jamming of the power cylinders due to ballistic impacts may occur through (1) flowering of cylinder and/or piston rod walls, (2) wedging of the round or round-generated debris in the piston head to cylinder bore or piston rod to gland clearances, and (3) collection of normal and/or damaged debris between the piston head and end glands.

There are several design approaches that take the above possibilities into account. One approach shown to be satisfactory through YUH-61A design and testing is to provide piston heads and end glands designed so that, when assymetrically loaded by wall flowering or debris, local sections fail and therefore permit piston displacement. This approach requires that the design provide piston head and gland sections which will fail, primarily in single shear, when assymetrically loaded. But, when symetrically pressure loaded, the design operates at a stress level that provides acceptable strength (ultimate and fatigue) and yield.

Another possible approach for piston head design would be to attach the piston head to the rod via a spherical joint with a shear pin between the rod and head. The design would have to be such that the normal axial loads would be transmitted through the spherical surface, but when loaded assymetrically in torsion, the shear pin would fail, permitting piston head rotation to generate piston-head-to-bore clearance in order to bypass the "flower" or debris. This approach is not suitable for low power actuators (small piston area) since the small difference between piston rod outside diameter and cylinder bore does not permit sufficient rotation of the piston head. The effects of the piston head design (required to give high bore clearance) on sealing methods would require investigation.

Designs making use of composites having high tensile properties but low shear properties can also be considered. The approach in this case would be to construct the cylinders so that the tensile properties of the filaments would provide good pressure vessel characteristics, but would permit shearing of "flowers" by the piston head due to low shear properties. This approach might also be taken for the piston rod so that a conventional gland design would be suitable. The significant problems to be considered in this approach would be development of cylinders and piston rods from composites to provide the required properties and the use of composite cylinders in a high surface wear environment.

For the particular requirements of the second-generation CH-47C, design studies based on a local failure section approach were conducted. These studies showed that due to the cylinder arrangement, the piston head diameter, and therefore the working areas, was driven by ballistic requirements, not by the power required. This resulted in a doubling of power output with a resultant increase in structural requirements for all associated rotor control hardware (swashplate and structural attachments) as well as an unacceptable increase in required installation space. Additionally, actuator power supply requirements would have to be increased in order to provide the same actuator performance characteristics. These drawbacks made the local failure section approach an undesirable candidate for reducing CH-47C vulnerability.

HYDRAULIC SYSTEM VOLUME

Introduction

Between the first and second generation of hydraulic systems, volume increased in proportion to system responsibilities. The first generation, with its small reactive loads and simple single-boost arrangement, had systems of very little volume. Even actuators, which were the most complex units in those systems, required little space. In some instances, the actuators were simply installed in-line with the mechanical controls, and accounted for little more volume than control rods.

The second generation, with its high reactive loads, dual power capability, and multiple utility hydraulic subsystems had greatly increased system volume. This was basically the result of using first-generation methods to accomplish the more varied and complex tasks of second generation helicopter hydraulic systems. This was necessary since new packaging concepts had not been developed and cost considerations made the use of off-the-shelf components attractive.

Third generation systems reversed the trend; volume was reduced via some use of modularization. Component volume did increase in particular third generation applications. In some cases various functions were consolidated in one unit, and at least one manufacturer interpreted the "fail-operational" requirement as requiring triple-redundant swashplate control actuators.

Throughout the generations, hydraulic system volume has not been an exceptionally critical consideration. Relative to jet fixed-wing aircraft, hydraulic system volume has had little impact on helicopter airframe envelopes. The prevailing procedure has been to locate hydraulic components wherever space exists.

Discussion

Third generation aircraft show some early design consideration for hydraulic component location. The trend towards modularized systems and their resultant larger components has been partly responsible for this new preplanning of hydraulic component locations. In the case of swashplate control actuators, the trend to modularization has resulted in large-volume actuators that include SCAS, valving, ballistics protection, and other functions. But, generally, compartment width is still controlled by other factors -- usually the size of the swashplate and the transmission. Basic determinants of transmission size are power transfer and speed reduction requirements. Swashplate size is influenced by vertical shaft diameter plus bearing and fitting envelopes. These components are, in turn, controlled by factors such as reactive loads and desired rotor geometry.

Because of transport requirements, the YUH-61A was designed with a minimum diameter swashplate. Yet, the swashplate control actuator with its integrated SCAS, three piston arrangement, and ballistic protection, had no direct influence on the airframe envelope. YUH-61A actuators were volume-restricted for another reason. In common with some other third-generation helicopters, the YUH-61A rotor transmission has reduced vertical dimensions in order to provide adequate cab... ceiling height within strict vertical fuselage envelopes. This trend may prove to be a major determinant of actuator longitudinal dimensions in at least some future helicopters.

HYDRAULIC SYSTEM COST

Introduction

Helicopter hydraulic system life cycle cost (LCC) can be separated into three categories:

1. Design-development
2. Acquisition
3. Operational

The first two groups are easier to document and evaluate. These are the costs that manufacturers have had to track and control since the first helicopter was sold. But actual operational costs are more difficult to document and evaluate; these are borne by the customer after acquisition. Manufacturers of military helicopters, until fairly recently, had

little real concern for all aspects of operational costs and therefore little incentive to collect and assimilate field data into the design process. This is no longer true. Manufacturers have developed LCC estimating tools that serve rather well when applied to the entire helicopter. But for detailed system comparisons, the present methods are not always adequate.

Design-Development Costs

A rough rule of thumb is that hydraulic system design-development costs are nine times the cost of one shipset of components. This expenditure can be apportioned at two different rates. The first approach has an early but low peak in design-development expenditures, followed by a gradual increase during the qualification stages. After that, the level of effort required to execute normal production changes is slightly less than the initial design effort. The second method results in a sharp, early rise in design-development expenditures, followed by a sharp fall through the qualification stages. This second curve represents the systems engineering approach that has been adopted by many fixed-wing transport manufacturers. This technique was also used during the UTTAS program. Total design-development costs may differ very little between the two methods, but the expected overall result is a total LCC savings, since MMH and spares costs are substantially lower. Front-loading of design-development expenditures allows the detailed examination of historical data for problem areas, and permits the application of knowledge gained to more rigorous trading of variables during early design stages.

In actual practice, the difference between the two methods is not always clear-cut. Many variables affect the outcome; these range from the initial aircraft production rate selected to the effectiveness of personnel executing the systems engineering approach. The systems approach becomes nearly valueless if inexperienced personnel perform the task, or if resistance to the effort exists at the program management level. Some fixed-wing transport manufacturers recognize these problems and provide for highly specialized, autonomous systems engineering groups, but this is difficult to accomplish without a stable employment situation.

The next generation of Army helicopters is expected to have constant-dollar design and development costs higher than those of today. Higher costs are expected in the area of qualification testing, since shortcomings in present testing

are evident (References 18 and 19). Additionally, the continued development of new technology such as modularized components, the expected application of at least some diagnostics, and generally more rigid reliability, maintainability, and safety requirements will all tend to increase design-development costs.

Acquisition Costs

Acquisition costs of hydraulic systems are more significant in larger utility-class helicopters and lighter helicopters in the medium lift category. Control loads are too great for manual systems, yet the hydraulic system cannot be scaled down for the relatively low loads. At one time only acquisition and design-development costs were considered when designing a system. With the introduction of LCC, the emphasis on acquisition costs has been slightly reduced but, it is probably still the prime cost consideration. This situation exists because in many areas, particularly hydraulic systems, LCC is difficult to assess. It is an intangible that will exist in the future, while acquisition costs are explicity known and must be dealt with immediately.

Figure 9 shows that 3000-psi flight control (FC) actuators cost about half as much as 1500-psi SAS actuators. This difference is accounted for by the compactness of the SAS units, plus the fact that low-pressure actuators are larger, and therefore more expensive than high-pressure actuators.

Third-generation FC actuators are substantially heavier than second-generation units, but perform more varied and complex functions. While FC actuators usually have SAS as an integral function, the FC actuator cost/weight characteristics overshadow the SAS cost/weight characteristics.

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[18] Bell, J. F., VALIDITY OF INDUCED ENVIRONMENT CRITERIA, The Boeing Vertol Company, USAAMRDL Technical Report 74-84, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, November 1974, AD 003324.

[19] House, T. L., and Artis, D. R., ENVIRONMENTAL EFFECTS ON ARMY HELICOPTER FLIGHT CONTROLS, U. S. Army Aviation Materiel Laboratories, Ft. Eustis, Va., Report A-71-15430, Presented before A. H. S., A. I. A. A., and University of Texas Joint Symposium on Environmental Effects on VTOL Designs, Arlington, Texas, 16-18 November 1970.

Utility hydraulic system actuator costs vary widely, but are generally lower than the FC actuator costs. This is due to the relatively noncomplex, noncritical nature of these actuators.

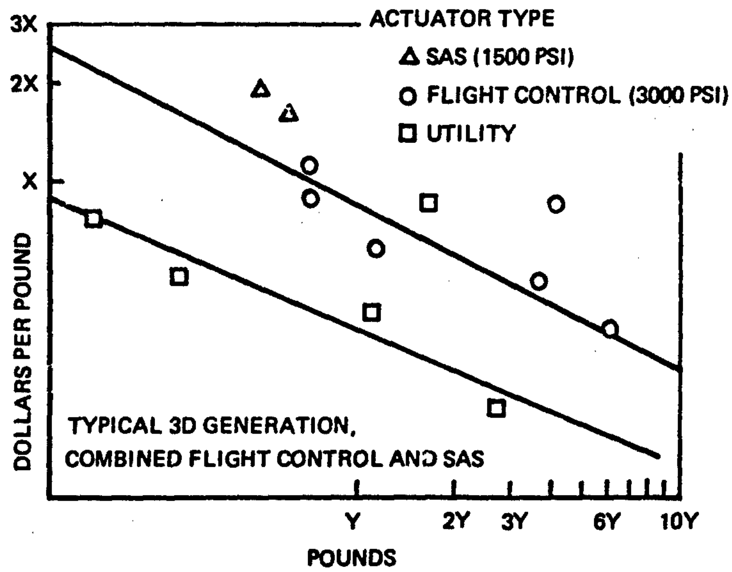

Figure 9. Acquisition Cost of Hydraulic Actuators.

Operational Costs

Operational costs are made up of a multitude of factors including costs of spares, component overhaul, system overhaul, GSE, MMH, flight crew manhours, and POL (fuel and oil) costs. Flight crew and POL costs are relatively stable for a given helicopter gross weight, class, and mission. Hydraulic system overhaul costs account for only a small portion of total aircraft overhaul costs.

Although variable according to system complexity, direct GSE costs usually are a minor part of life-cycle costs. Third-generation system designers have generally made a strong effort to reduce GSE requirements, primarily to improve maintainability by reducing reliance on equipment that is not always available, and to decrease the Army's logistics burden.

Hydraulic pump and accumulator costs are the same whether the unit is installed in the flight control or the utility system. Informal estimates by pump and accumulator manufacturers indicate that acquisition costs of these items have increased approximately 10-20% since 1965 when measured in constant dollars.

Pump manufacturers believe that their costs have increased because of:

1. More stringent military specification requirements, particularly in the area of testing.

2. Smaller volume bases due to fewer aircraft being built as compared to the era of second-generation hydraulic systems.

Accumulator costs have risen primarily because of a shrinking volume base and specification changes. The accumulator volume base has decreased more than the pump volume base because increased emphasis is now being placed on designing hydraulic systems with fewer accumulators.

MMH and spares account for a significant portion of operational costs. Figure 10 shows the man-hour and spares costs for a medium lift helicopter (MLH). Some may argue that spares comprise a larger share of hydraulic systems cost, but the presented data is accurate within reasonable limits. Generally, the greatest cost savings will occur when reliability is improved, since a dual benefit is realized; i.e., spares costs are reduced and man-hours decreased. There are subtle factors, generally believed to impact only MMH costs, that also affect spares costs to a significant degree. System complexity and diagnostics are examples; many trade studies fail to consider the spares cost impact of system complexity and inadequate diagnostics. These can account for a sizable increase in spares costs, as well as MMH costs and helicopter availability. The earlier maintainability state of the art discussion noted that more than 20% of helicopter components returned for overhaul through supply had no defects, and estimated that the percentage was much higher for hydraulic components. Since spares costs is a large contributor to operational costs, this is clearly an area of potential improvement.

"No defect" removals and fault isolation time are just two facets of the issue involving modularization and diagnostics, and their impact on LCC. Helicopter hydraulic system designers are in need of guidelines to help determine the correct balance of modularization and diagnostics that will achieve minimum LCC. The total LCC picture has never been explored in the detail necessary to identify the optimum balance. For instance, what is a 1% increase in availability worth? Presently, there is no costing tool in current use to assess the impact of availability on LCC. The following is one suggested method of costing availability: If a fleet of 600 helicopters were operating at 80% of availability, and that availability was improved by one-half of one percent (to 80.5%), then, theoretically, 596 helicopters could perform

the same fleet task that formerly required 600 helicopters. Would there be any cost benefit involved? If there is, then is that benefit more or less than the acquisition costs of four helicopters? At least one study is currently working toward an answer to these questions (Reference 20).

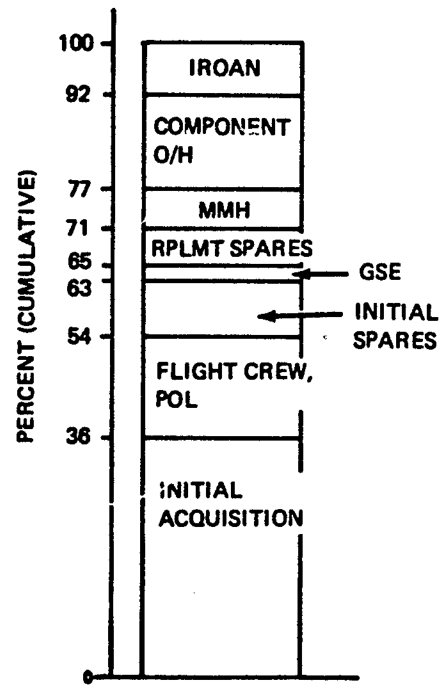

Figure 10. Typical Life-Cycle Cost Apportionment for a Medium Lift Helicopter.

HYDRAULIC SYSTEM WEIGHT

Introduction

Weight has always been a prime consideration in fixed-wing and helicopter design programs, and hydraulic system weight is no exception. In earlier helicopter generations, weight

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[20]Blewitt, S. J., PRODUCT IMPROVEMENT PROGRAM EVALUATION, The Boeing Vertol Company, Document D210-11146-2, Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, VA, Contract DAAJ02-76-C-0020, February 1977.

along with acquisition costs received consideration nearly to the exclusion of all other factors except safety. Today's emphasis on LCC, plus the availability of powerful turbine engines, have resulted in the absorbtion of some weight penalties to provide gains in other areas, but weight is still a prime consideration during the design effort. Usually, large contractual penalties and incentives depend on meeting or bettering the design weight target.

Various activities have performed specialized studies to determine what a pound of empty aircraft weight is worth. In particular, airframe manufacturers have calculated what a pound was worth relative to their available resources. This study is concerned with the worth of a pound, in dollars, to the U. S. Army. A study by Dr. Gene R. Marner, of the RD&E Directorate at AVSCOM, indicated that for a composite Army helicopter fleet, the benefit, per aircraft, over the life of the aircraft, is an average of $3,000 for the weight reduction of one pound (Reference 21). A number of variables are involved in this calculation including fleet life, and yearly flight activity. The latest predictions for UTTAS yearly flight hours has somewhat lowered the fleet average. Using Dr. Marner's formula, with inputs for a typical MLH with a fleet life of 15 years, would yield a worth of $650 for each pound reduction in airframe weight.

Single-boosted first-generation helicopter hydraulic systems accounted for a relatively small percentage of the empty airframe weight. Today, typical combined weights of utility and flight control hydraulic systems for second- and third-generation helicopters are approximately 800 lb for an MLH of 33,000 lb design gross weight and 400 lb for a large utility-class helicopter of 15,000 lb design gross weight. Ranked according to weight, the heaviest component groups in a typical tandem rotor MLH utility hydraulic system usually are:

1. Plumbing
2. Accumulators
3. Pumps and motors
4. Actuators

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[21] Marner, Dr. G. R., BENEFITS TO HELICOPTER USERS WHICH [illegible] FROM REDUCTIONS OF WEIGHT, POWER CONSUMPTION AND FAILURE RATE, U. S. Army Aviation Systems Command, 1975.

For FC systems, the weight rankings are:

1. Actuators
2. Plumbing
3. Supports
4. Pumps and motors

Discussion

Weight differences due to modularization depend on the overall size of the aircraft, the functions and degree of modularization involved, and the hydraulic power levels required. A study by Ling Temco Vought (LTV) Corporation of an A-7 control system showed a 30% weight increase by redesigning the system to a power-by-wire IAP hydraulic system (Reference 22). This is an example of the highest level of modularization.

In general, a weight increase can be expected whenever a multiplicity of small pumps and electric motors are used instead of one single large, mechanically-driven pump. In the case of the power-by-wire IAP where several forms of power must be utilized, i.e., mechanical to electrical to mechanical to hydraulic, a major efficiency loss is normal and a significant weight increase can be expected. For this, among other reasons, the IAP probably is not the most acceptable configuration for 3000/4000-psi systems using state-of-the-art technology.

A number of studies have been performed by the aerospace hydraulic industry to determine the optimum pressure for reducing the weight of nonmodularized hydraulic systems. These studies indicated that various pressures, ranging from 3500 to 8000 psi, provided the lowest weight. The exact pressure depended upon the total length of fluid lines in the circuit and power requirements. The studies indicate that the many variables involved make each case an entity and that no generalized rule can apply. Pressure level applicability is discussed in more detail in the section of this report that deals with VHP system benefits and drawbacks.

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[22] Koch, W. G., RESEARCH AND DEVELOPMENT OF AN INTEGRATED SERVO ACTUATOR PACKAGE FOR FIGHTER AIRCRAFT, LTV Electrosystems, Inc., Arlington Plant; AFFDL Technical Report 69-109, U. S. Air Force Flight Dynamics Laboratory, U. S. Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, November 1969.

STATE-OF-THE-ART CONCLUSIONS

Most hydraulic system problems can be solved using state-of-the-art technology. Employing increased degrees of modularization would ease or resolve many of those problems, but the proper tools to identify the cost savings associated with modularization presently do not exist. The following areas require further development and should have solutions well within the present technology base.

PRESENT PROBLEMS THAT REQUIRE FURTHER DEVELOPMENT WITHIN THE STATE OF THE ART

SUMMARY

PROBLEMS	EXISTING SOLUTIONS	FURTHER WORK
Plumbing leaks impact reliability, maintainability, safety and cost.	Reduce leak points by component modularization and by swaging line connections. Use new fitting designs.	Develop program to optimize usage of modularization and diagnostics.
Fault isolation difficulties result in false removals that impact maintainability and cost.	Design systems with better fault isolation characteristics, including new diagnostics.	
Seal life impacts reliability, maintainability, safety, and cost.	Improved (5-15 micron) filtration to reduce contamination; use state-of-the-art scraper rings, and include actuator seal boots for extreme environmental situations.	Develop seal concepts and materials. Investigate relationship between seal wear and contamination in the range of 5 microns and lower. Develop improved scraper seals.

DEVELOPMENT OF VHP TECHNOLOGY

INTRODUCTION

The Columbus Aircraft Division (CAD) of Rockwell Corporation began work on the VHP concept in 1966 with a theoretical analysis of factors associated with the development of very high pressure fluid power systems for aircraft. Work then progressed in logical steps from theoretical considerations to a weight savings study to evaluation of experimental hardware to endurance testing (References 23 through 30). A flight-test program is currently underway.

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[23] Deamer, D., and Brigham, S., THEORETICAL STUDY OF VERY HIGH PRESSURE FLUID POWER SYSTEMS, NA66H-822, North American Aviation, Inc. Columbus Division, 15 October 1966.

[24] Stauffer, J., DYNAMIC RESPONSE OF VERY HIGH PRESSURE FLUID POWER SYSTEMS, NR69H-65, North American Rockwell Corporation, Columbus Division, 9 December 1970.

[25] Demarchi, J., DYNAMIC RESPONSE TEST OF VERY HIGH PRESSURE FLUID POWER SYSTEMS, NR70H-533, North American Rockwell Corporation, Columbus Division, 9 December 1970.

[26] Demarchi, J.N., and Haning, R.K., APPLICATION OF VERY HIGH PRESSURE HYDRAULIC SYSTEMS TO AIRCRAFT, NR72H-20, Columbus Aircraft Division, North American Rockwell Corporation, March 1972.

[27] Demarchi, J.N., and Haning, R.K., LIGHTWEIGHT HYDRAULIC SYSTEM DEVELOPMENT, NR73H-20, Columbus Aircraft Division, Rockwell International Corporation, May 1973.

[28] Demarchi, J.N., and Haning, R.K., PREPARATIONS FOR LIGHTWEIGHT HYDRAULIC SYSTEM HARDWARE ENDURANCE TESTING, NR73H-191, Columbus Aircraft Division, Rockwell International Corporation, December 1973.

[29] Demarchi, J.N., and Haning, R.K., LIGHTWEIGHT HYDRAULIC SYSTEM HARDWARE ENDURANCE TEST, MR75H-22, Columbus Aircraft Division, Rockwell International Corporation, March 1975.

[30] Demarchi, J.N., and Haning, R.K., DESIGN AND TEST OF AN LHS LATERAL CONTROL SYSTEM FOR A T-2C AIRPLANE, NR76H-14, Columbus Aircraft Division, Rockwell International Corporation, May 1976.

A program for the development of advanced flight control actuation systems (AFCAS) was begun at CAD in 1972 (References 31 through 34). This work involved the integration of three separate concepts: (1) fly-by-wire, (2) building-block actuators, and (3) localized hydraulic power (8000 psi). Phase V, currently in progress, includes the installation and flight testing of a fly-by-wire 8000-psi rudder actuator in a T-2C airplane.

ANALYSIS AND DESIGN

Several design parameters are affected by operating pressure level--in particular: fluid viscosity, actuator stiffness, pressure surges, and heat generation. The degree to which 8000 psi (versus 3000 psi) affects these parameters and thus system performance was a primary concern. Laboratory investigations were begun in 1968, and since then many hundreds of hours of testing have provided new insights into the effect of high pressure on these parameters.

FLUID VISCOSITY

Viscosity is directly related to tubing pressure losses and component internal leakage rates. Temperature has a marked influence on fluid viscosity; pressure has a less pronounced effect. Classic fluid flow theory for pressure drop, orifice flow, capillary flow, etc., is applicable at 8000 psi. Thus, procedures used at 3000 psi to determine line losses, orifice sizes, and valve dimensions are also valid at 8000 psi.

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[31] FEASIBILITY STUDY FOR ADVANCED FLIGHT CONTROL ACTUATION SYSTEM (AFCAS), NR72H-240, Rockwell International Corporation, Columbus Aircraft Division, June 1972.

[32] CONTROL-BY-WIRE ACTUATOR MODEL DEVELOPMENT FOR AFCAS, NR73H-107, Rockwell International Corporation, Columbus Aircraft Division, January 1974.

[33] CONTROL-BY-WIRE MODULAR ACTUATOR TESTS (AFCAS), NR75H-1, Rockwell International Corporation, Columbus Aircraft Division, January 1975.

[34] DESIGN AND FABRICATION OF AN 8000-PSI CONTROL-BY-WIRE ACTUATOR FOR FLIGHT TESTING IN A T-2C AIRPLANE (AFCAS), NR76H-1, Rockwell International Corporation, Columbus Aircraft Division, January 1976.

For a given temperature, fluid viscosity is higher at 8000 psi than at 3000 psi. The effect of this increase on line losses is not significant when viewed from the standpoint of transmitted horsepower. At normal operating temperatures, +120° to +220°F, line losses at 8000 psi are generally less percentage-wise than at 3000 psi. Typical pressure drops in tubing at 3000 psi and 8000 psi are compared below, based on a given horsepower level, 15 ft/sec fluid velocity at 3000 psi, and using MIL-H-83282 fluid.

Operating Pressure (psi)	Tube Size (in.)	Fluid Velocity (ft/sec)	Horsepower Transmitted	% Loss of Sys Press. per Foot of Tubing		
				0°F	+100°F	+200°F
3000	3/8 x .022	15	7.05	1.33	.059	.050
8000	1/4 x .025	15.4	7.05	2.41	.098	.041
3000	1/2 x .029	15	12.57	.75	.034	.035
8000	3/8 x .038	12	12.57	.66	.035	.017

Viscosity affects internal leakage across lapped fits in hydraulic components. Special fits and tolerances were not required to maintain acceptable internal leakage rates in the experimental hardware tested by CAD. The pumps, actuators, and valves built for the VHP and AFCAS programs were designed using conventional clearances and tolerances; internal leakage rates observed were nominal. Therefore, viscosity increase due to pressure appears to have a beneficial effect on leakage through small clearances.

ACTUATOR STIFFNESS

Weight savings produced by operating at 8000 psi instead of 3000 psi begins with smaller net areas on actuator pistons. Lower flow demand because of less displaced fluid results in a general decrease in the size of supply lines, pumps, reservoirs, etc. Use of smaller piston area, however, reduces actuator physical stiffness which in turn lowers system resonant frequency. Mechanical elements that contribute to physical stiffness include bearings, piston/rod, cylinder, and actuator end pieces; hydraulic elements are the fluid and seals. Based on practical experience, it has been found that actuator physical stiffness is approximately equal to the stiffness due to fluid bulk modulus.

Thus,

$$K_f \approx \frac{4\beta_f A\eta}{S}$$

where: K_f = Stiffness due to fluid compressibility (actuator piston at mid-stroke)

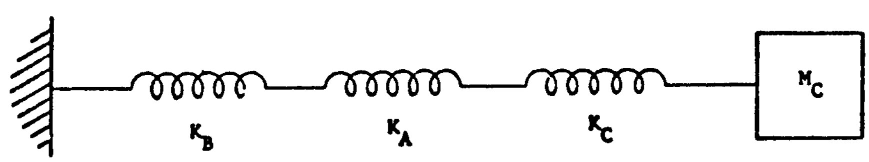
β_f = Bulk modulus of fluid (taken at one-half system pressure, approximately 15% higher at 4000 psi than at 1500 psi)

A = Piston net area

S = Piston Stroke (total)

η = Ratio of fluid volume swept by the piston to the total fluid volume contained between the piston and control valve, typically between 0.85 and 0.95 for an integrally mounted valve

In a practical hardware installation, the actuator backup structure, the actuator, and the control surface are three significant springs, as shown below. Control surface inertia is the only significant mass. The three springs are in series, anchored to the aircraft at one end and supporting the mass at the other. If the spring rates of each are assumed equal, then the actuator is twice as stiff as the combined structure/surface spring. Normally, however, the actuator is the stiffest spring in the system.



where: K_B = Backup structure spring rate

K_A = Actuator spring rate

K_C = Control surface spring rate

M_C = Control surface mass

Now, $\frac{1}{K_T} = \frac{1}{K_B} + \frac{1}{K_A} + \frac{1}{K_C}$

where: K_T = Net total spring rate

Let $\frac{1}{K_{BC}} = \frac{1}{K_B} + \frac{1}{K_C}$

if $K_A = K_B = K_C$

Then, $K_A = 2K_{BC}$

System natural frequency is established by net total stiffness and varies with the square root of the stiffness.

$$\omega_n = \frac{K_T}{M_e}$$

where: ω_n = System undamped natural frequency

K_T = System net spring rate

M_e = Effective mass

Physical stiffness is the composite effect of mechanical and hydraulic compliant elements between the actuator mounting points. Actuator functionsl stiffness is due to closed-loop servo action, and is related to loop gains and control valve performance characteristics. In a conventional position feedback system, functional static stiffness is higher than physical stiffness.

Frequency response tests of similar sized power actuators operating at different pressure levels were conducted in a rigid mass load fixture (Reference 25). Damped natural frequencies observed were:

Actuator	Operating Pressure	Resonant Frequency
CAD P/N 247-58716	3000 psi	27 Hz
CAD P/N 4212-01	6000 psi	24 Hz
CAD P/N 4212-01	9000 psi	22 Hz

Performance characteristics of the 6000- and 9000-psi actuators were very similar to the 3000-psi actuator for large amplitude, manual-type inputs. For small amplitude inputs, such as those encountered with automatic control, response capabilities of the 6000- and 9000-psi actuators were satisfactory to 10 Hz. The reduction in resonant frequency noted above was not considered critical.

A VHP study conducted on the F-14 airplane disclosed that only 4 out of 58 actuators were stiffness sensitive (Reference 26). If the design of these four actuators could have been optimized for VHP, i.e., piston diameter, horn radius, and stroke length, some weight savings could have been realized without a significant loss in stiffness.

Although actuator physical stiffness is fundamentally reduced by going to higher operating pressures, this is partially offset by an increase in fluid bulk modules. The net reduction should not degrade system performance significantly in conventional applications because of lesser stiffness in backup structure and linkages. Furthermore, control techniques are available to offset lag effects caused by reduced stiffness.

PRESSURE SURGES

Pressure surges are normal in aircraft hydraulic systems and are an important design parameter because of their effect on the fatigue and functional characteristics of system components. Surges result primarily from:

1. Sudden stopping of high-velocity fluid
2. Sudden porting of high-pressure fluid into a chamber filled with low-pressure fluid
3. Bottoming of an actuator piston
4. External energy derived from load inertia

When the flow of a mass of fluid is suddenly decelerated by a rapidly closing valve, water hammer results; this is usually the most severe pressure transient encountered in hydraulic circuits. Assuming instantaneous valve closure, this surge may be calculated by

$$\Delta P = V\sqrt{\rho \beta_e}$$

where: ΔP = Maximum pressure rise above system pressure

V = Fluid velocity

ρ = Fluid mass density

β_e = Effective bulk modulus (fluid compressibility + tube elasticity)

Pump response time is also a factor causing surges. Operation of the delivery control mechanism normally occurs in 0.050 sec. or less. Thus, when a valve closes, the pump momentarily continues to discharge fluid until the control mechanism adjusts to the new flow demand; this can result in a pressure overshoot.

Surges in 8000 psi systems are less, percentage-wise, than in 3000 psi systems because of:

1. Better damping at 8000 psi due to increased fluid viscosity.
2. The minor effect of operating pressure level on water hammer magnitude (ρ and β_f).
3. Faster pump response at 8000 psi.

Typical peak surges observed in a laboratory system designed and operated to compare surges at 3000 and 8000 psi are listed below: (References 25 and 26).

System	Peak Pressure	Overshoot
3000 psi	3900 psi	130%
8000 psi	9200 psi	115%

The maximum allowable surge in 3000 psi systems is 135%, reference MIL-H-5440. The maximum allowable surge in 8000 psi systems was established at 120% in Reference 26. The validity of the 120% design value has been confirmed by laboratory testing.

HEAT GENERATION

Hydraulic systems generate heat because it is impossible to convert all input power into useful work. Thus, hydraulic systems normally operate at temperatures above ambient. Temperature stabilization is reached when the heat loss rate equals the generation rate. Fluid temperatures must be maintained within the fluid temperature envelope to prevent thermal breakdown of the fluid and seals. For Type II systems the maximum temperature is +275°F (MIL-H-5440); for Type III systems it is +390°F (MIL-H-8891). If heat dissipation through conduction, radiation, and convection is not sufficient to maintain reasonable fluid temperatures, then a heat exchanger is required. A hydraulic system must be designed so that a heat balance is achieved at a satisfactory operating temperature.

The principal sources of heat generation in hydraulic systems are:

1. Pump and valve internal leakage.

2. Orifices and valves used to throttle and control flow. (These devices are inherent heat generators.)

3. Resistive pressure drops in lines, fittings, and porting passageways.

The principal means of heat dissipation are:

1. Conduction from hydraulic system components through attachments into aircraft structure.

2. Convection aided by air flow around surface areas of system components.

3. Radiation from system components.

Since operating temperatures are related directly to the surface area of a hydraulic system, cooling requirements will be somewhat greater at 8000 psi due to the inherent compactness and reduction in the exposed area of the system (assuming 3000 psi and 8000-psi pump efficiencies are the same). Therefore, 8000-psi systems must be designed to operate at slightly higher ΔT allowables.

A principal heat generator in an aircraft hydraulic system is the pump. High operating efficiency is therefore essential to minimize heat rejection. Overall efficiency levels of conventional 3000 psi, variable delivery, aircraft-type pumps generally range from 85 to 92% depending on operating conditions.

The 8000 psi pumps developed for the VHP program have overall efficiency levels similar to 3000 psi units (References 27 and 30).

$$HR = Q \times C_p \times \Delta T$$

where: HR = Heat rejected to hydraulic system, Btu/min

Q = Case drain flow, lb/min

C_p = Fluid specific heat, Btu/lb/°F

ΔT = Fluid temperature rise, °F

At rated operating conditions, case drain fluid temperature is usually about 40°F above the inlet temperature for 3000 psi pumps, and about 50°F for 8000 psi pumps. The theoretical temperature increase based on throttling within the pump can be calculated by

$$\Delta T = \frac{\Delta P}{3.6 \times 10^6 \times \rho \times C_p}$$

where: ΔT = Fluid temperature increase due to throttling

ΔP = Throttling pressure drop, psi

ρ = Fluid mass density, $lb/sec^2/in^4$

C_p = Fluid specific heat, Btu/lb/°F

The theoretical fluid temperature rise due to internal leakage is thus about 20°F for a 3000 psi pump and 50°F for an 8000-psi pump. Performance data indicate, however, that other factors make significant contributions to case drain fluid temperatures, such as viscous (windage) losses, coulomb friction, and inherent cooling leakage.

HARDWARE DEVELOPMENT

Introduction

Several companies cooperated with CAD during the development of components used in the VHP and AFCAS programs.

COMPANY	HARDWARE
Aerospace Division of Abex Corporation	Pumps
Sterer Engineering and Manufacturing Company	Solenoid valves
PneuDraulics, Incorporated	Relief valves
The Lee Company	Restrictors
W. S. Shamban and Company	Seals
Greene, Tweed and Company	Seals
Cook-Airtomic Division of Dover Corporation	Seals
Rosan, Inc.	Fittings
Resistoflex Corporation	Fittings and hoses
Titeflex Division of Atlas Corporation	Hoses

Hardware items to be discussed in this section include the pump, fluid, seals, actuators, fittings, hoses and tubing.

Pump

Two variable delivery designs have been built for use in the VHP and AFCAS programs:

Quantity	Model No.	Rated Performance
3	AP6V-57	14 gpm at 7850 psi and 4000 rpm
1	AP1V-106	3 gpm at 7850 psi and 7330 rpm

Both 8000-psi models were developed from existing hardware. No effort was made to optimize the designs or to minimize weight; cost was a primary concern. No significant problems were encountered in their development. Both models functioned satisfactorily and had overall efficiency levels of approximately 90%. Total operating time (as of 1 July 76) on the pumps is summarized below:

M/N	Total Accumulated Running Time, Hours	Tes' ˊ ɪg Conducted By
AP6V-57, No. 1	206	CAD
AP6V-57, No. 2	106	CAD
AP6V-57, No. 3	450 (Approx)	NADC
AP1V-106	52	CAD

Pump endurance has not yet been fully explored.

Hydraulic Fluid

Lightweight hydraulic system development test ɪg was conducted initially (in 1968) using MIL-H-5606 (Referen : 24). This fluid exhibited poor shear stability due to polymeric additives employed to improve its viscosity-temperature coefficient. MIL-H-27601 was used for the tests reported in Reference 25 and 26 because of its excellent shear stability. MIL-H-27601 is a high-temperature hydraulic fluid and very viscous at low temperatures. MIL-H-83282 was subsequently evaluated as a possible candidate for 8000-psi systems (References 29, 35, and 36). This fluid is rated for use at temperatures from -50° to +400°F, is shear stable, and is less flammable than MIL-H-5606. Physical properties of MIL-H-83282 are given in Reference 37.

Shear stability is particularly important in a fluid required to operate at high pressure levels. A non-Newtonian fluid, such as MIL-H-5606, can experience either temporary or permanent viscosity losses when it is subjected to high shear rates. Temporary losses occur during laminar flow. Permanent

[35] Dever, J.H., SELECTION AND EVALUATION OF MIL-H-83282 HYDRAULIC FLUID FOR USE IN LIGHTWEIGHT HYDRAULIC SYSTEM (8000 PSI), NADC-74154-30, Naval Air Development Center, AIRTASK No. A3400000/001B/4F41433402, 2 July 1974.

[36] Herr, J.L., and Pierce, N.J., EVALUATION OF MLO-68-5 LESS FLAMMABLE HYDRAULIC FLUID, ASD-TR-70-36, McDonnell Aircraft Company, McDonnell Douglas Corporation, September 1970.

[37] PHYSICAL PROPERTIES OF HYDRAULIC FLUIDS, AIR 1362, Society of Automotive Engineers, Inc., May 1975.

losses can result from severe turbulence, cavitation, and large pressure drops across sharp-edged orifices. These conditions can stress molecular chains to the breaking point, resulting in a less viscous fluid. At high operating temperatures, reduced viscosity causes increased power losses due to higher internal leakage rates, and increased wear (viz. pumps) due to less lubricity.

MIL-H-83282 is a synthetic hydrocarbon and has exhibited excellent shear stability and lubricity characteristics in tests conducted at 8000 psi by CAD and the Naval Air Development Center. Further testing is required to establish MIL-H-83282 as a satisfactory fluid for extended usage in lightweight hydraulic systems.

Seals

An industry-wide survey was conducted by CAD to find candidate seals for lightweight hydraulic systems (Reference 26). Twenty-two different types were selected for endurance testing in seal test fixtures. During 100 hours of cycling at 8000 psi and +200°F, static seals were exposed to 880,000 pressure pulsations and dynamic seals were subjected to 440,000 piston oscillations. A summary of results is given below. Detailed results are in Table 9.

Seal Type	Number of Satisfactory Seals (No Gross Leakage)	Number of Unsatisfactory Seals
Piston	3	0
Piston Rod	5	0
Diametral	3	2
Face	[illegible]	1
Boss	3	2
Totals	17	5

Based on endurance testing conducted thus far, the following are considered possible 8000-psi seal candidates by CAD:

Seal Type	Manufacturer
Metallic (split rings)	Cook-Airtomic
Double-Delta	Shamban
G-T Seal	Greene, Tweed

Conventional elastomeric o-rings proved to be satisfactory as static seals. Standard Teflon backup rings were employed successfully in diametral glands.

TABLE 9. SEAL TEST RESULTS

SEAL TYPE	LOCATION	PART NUMBER	SUPPLIER	LEAKAGE								RESULTS
				0 HOURS		16 HOURS		50 HOURS		100 HOURS		
				100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI	100 PSI	8000 PSI	
Piston	A	123DX-2040	Cook Airtomic	6.9 CC/M	2.9 CC/M	9.5 CC/M	55 D/M	15.5 CC/M	12 D/M	26.4 CC/M	59 D/M	S
Piston	F	7330MT-160-9009	Greene, Tweed	T*	1 D/2M	5 D/M	1 D/M	T	T*	0	T	S
Piston	F	S20860-330	Shamban	1 D/M	T*	0	1 D/M	T	T	32 CC/M	14 D/M	S
Rod	A	SP-4246-4-162	Cook Airtomic	3 D/M	6 D/M	3 D/2M	2 D/M	T*	2* D/M	2 D/M	3 D/M	S
Rod	F	507-1.250G	Bal-Seal	0	0	0	0	0	0	T	T	S
Rod	F	7218FT-160-9009	Greene, Tweed	0	0	4 D/M	6 D/M	0	0	T*	1 D/2M	S
Rod*	F	S13122-218	Shamban	T	0	0	0	2 D/M	0	T	1 D/M	S
		NAS 1593-218	Parker									
Rod	F	S20865-218	Shamban	0	0	0	0	0	0	0	T	S
Diametral	F	505-2336	Bal-Seal	T*	T	0	0	0	0	0	0	S
Diametral*	F	NAS 1593-233	Parker	T	0	0	0	0	0	0	2 D/M	U
Diametral	F	S31120-4	Shamban	0	0	0	0	0	0	0	0	S
Diametral	F	U-2410-03125-SED	United Aircraft	T	T	1 D/M	10.5 CC/M	1 D/M	11.1 CC/M	7.2 CC/M	2?0 CC/M	U
Diametral	A	NAS 1593-116	Parker	LEAKAGE NOT MEASURED ***								
		MS 28774-116										
Face	F	5484-32900-160-0220	Greene, Tweed	T	0	0	0	0	0	T	T	S
Face	F	664A9X-0034-1	Pressure Science	T	T	0	0	0	0	T	T	S
Face*	F	4252-03-25	Rockwell	T	0	0	0	0	0	T	T	S
		NAS 1593-227	Parker									
Face	F	U-2410-02375-SED	United Aircraft	T	0	0	0	0	0	T	1 D/2M	U
Boss*	F	NAS 1596-06	Parker	0	0	0	0**	0	0	0	0	S
Boss	A	S31121-6	Shamban	0	0	0	0	0	0	0	0	S
Boss	F	U-700413-062	United Aircraft	0	0	0	0	0	T	0	T*	U
Boss	F	U-700413-063	United Aircraft	0	0	0	0	0	T*	0	1 D/5M	U
Boss	F	NAS 1593-012 (RF 9906-13)	Parker (Rosan Fitting)	0	0	0	0	0	0	0	0	S

ABBREVIATIONS

A LHS ACTUATOR
CC CUBIC CENTIMETER
D DROP (FLUID)
F SEAL TEST FIXTURE
M MINUTE (TIME)
S SATISFACTORY
T TRACE
T* LESS THAN ONE DROP
U UNSATISFACTORY

* SEAL DESIGNED BY ROCKWELL/COLUMBUS

** SEAL REMOVED AT 16 HOURS DUE TO INCIPIENT FAILURE. PROBLEM ATTRIBUTED TO ROUGH SURFACE ON MS 21902-6 FITTING. BOTH FITTING AND SEAL REPLACED.

*** SEAL CONDITION SATISFACTORY AT 100 HOURS

Actuators

Four 8000-psi servo actuators have been designed and built by CAD, as described in Table 10. Two of the units, P/N 4212 and P/N 4257, were for the VHP program; P/N 4248 and P/N 4262 were for the AFCAS program.

TABLE 10. 8000-PSI ACTUATORS DESIGNED AND BUILT AT CAD

CAD P/N	TYPE	INPUT	MID-STROKE LENGTH, IN	PISTON STROKE, IN	MAX. OUTPUT FORCE
4212	For lab tests, dual system tandem, balanced piston	Manual	46.2	8.2	26,000 lb/chamber
4248	For lab tests, dual system tandem, partially balanced, modular construction	Electrical (torque motor driven valve)	38.3	8.2	46,000 lb extend 36,000 lb retract
4257	For T-2C aileron, single system, balanced piston	Manual	15.2	3.0	1870 lb
4262	For T-2C rudder, single system, balanced piston, modular construction	Electrical (torque motor driven valve)	16.6	3.5	1870 lb

A principal CAD objective has been to show that 8000-psi actuators can be built to meet specific performance requirements using conventional design practices and manufacturing procedures. Although component weight reduction is the fundamental reason for the VHP program, no attempt was made to optimize the actuators; cost was a primary consideration.

Each of the 8000-psi actuators has an integrally mounted, single-stage, spool/sleeve-type flow control valve. Two-stage rod seals and three-piece metallic piston seals were used in all units. Each actuator configuration was defined by (1) program objectives, (2) maximum hinge moment, (3) stroke length, (4) maximum piston velocity, (5) available space, and (6) dynamic performance requirements.

Detail design procedures were similar to those employed for 3000-psi units. Actuator cylinder walls were sized for burst; rods were designed for column buckling. Piston areas were sized so that full load could be carried at rated speed with a differential pressure across the piston of 2/3 system pressure. Fluid volume between the control valve and actuator was kept small to maximize actuator stiffness. Design of the control valve orifices was conventional. Spool/sleeve

clearances and tolerances were the same as those used for 3000 psi units. Valve overlap (0.002 in.) was employed to insure stability at null and to minimize internal leakage.

Control valve performance was expected to be a problem at 8000 psi because of (1) high internal leakage and (2) metering edge erosion. These problems did not develop. Null power loss has been nominal--generally less than 0.12 hp. Similar losses occur in 3000-psi valves (Reference 25). Valve erosion has been negligible. The use of MIL-H-83282 fluid may have contributed to valve performance through its excellent shear stability and lubricity characteristics.

Operation of the 8000-psi actuators was, from outward appearances, identical to similar sized 3000 psi units. Spool flow forces were low, output piston motion was easily controlled, resolution was excellent, and dynamic response was more than adequate. Actuator endurance is one area yet to be examined. Endurance testing will provide important information on seal performance, control valve wear, and fatigue of structural elements.

Fittings

Resistoflex Dynatube series fittings have been evaluated in both the VHP and AFCAS programs. Results have been satisfactory thus far. Resistoflex Corporation conducted tubing flexure tests at 8000 psi on titanium fittings swaged to 20-6-9 tubing with successful results (Reference 30).

The Naval Air Development Center conducted flexure and impulse tests on Dynatube fittings welded to titanium tubing in general agreement with MIL-F-18280. The impulse pressure peak was 10,800 psi (135% of 8000 psi). The fittings satisfactorily withstood both the flexure and impulse tests and subsequent burst pressure testing at 24,000 psi (Reference 38).

Titanium Rosan fluid connectors were evaluated in the VHP and AFCAS programs. Performance at 8000 psi has been satisfactory.

Standard MS type flareless steel fittings have been used almost exclusively in the 8000 psi portion of all VHP systems built and tested in the CAD engineering laboratory. These fittings are, of course, designed for 3000 psi aircraft systems. No problems whatsoever have been encountered using these fittings at 8000 psi. It should be noted, however, that aircraft vibrations were not simulated during the laboratory tests.

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[38] Dever, J.H.; EVALUATION OF BRAZED PERMANENT AND WELDED SEPARABLE TYPE CONNECTORS AND TITANIUM TUBING FOR USE IN LIGHTWEIGHT HYDRAULIC SYSTEMS (LHS), 8000 PSIG, NADC-76067-30, Naval Air Development Center, AIRTASK No. A3400000/001B/4F4-1433402, 7 June 1976.

Hoses

Titeflex series 370 and Resistoflex series R44598 have been subjected to endurance testing at 8000 psi (Reference 29). Performance has been satisfactory. These hoses have a 24,000-psi burst pressure and Dynatube end fittings.

Tubing

A burst pressure of 3 x 8000 psi = 24,000 psi for VHP tubing was selected by CAD in 1972 (Reference 26). Tubing burst pressure in conventional 3000-psi systems is 4 x 3000 = 12,000 psi. A burst factor (BF) of 3.5 was used in this study. The rationale that CAD originally used to develop a 3.0 burst factor for VHP systems was based on two major parameters which are affected by operating pressure level: pressure surges and tubing wall thickness.

The pressure surge associated with instantaneous (fast-acting) valve closure is primarily a function of fluid velocity, density, and bulk modulus as shown below:

$$\Delta P = V\sqrt{\rho\beta_e}$$

Since fluid density and bulk modulus are only slightly affected by operating pressure level and both terms are under the radical, their combined influence on surge magnitude is only about 10% greater at 8000 psi than at 3000 psi. This has been verified by laboratory testing. Peak surges measured in VHP systems average around 1200 psi at +200°F and 25 ft/sec fluid velocity (Reference 27); this represents a surge of 115%. To be conservative, the maximum allowable peak surge in 8000 psi systems was established as 120%. The maximum allowable surge in 3000 psi systems is 135% (1050 psi), reference MIL-H-5440.

The change in allowable surge from 135% in 3000-psi systems to 120% at 8000 psi results in an equivalent burst factor of 3.5 for VHP systems as shown below:

3000-psi System:

$$\frac{\text{Burst Pressure}}{\text{Max. Allowable Surge Pressure}} = \frac{4 \times 3000}{1.35 \times 3000} = 2.96$$

8000-psi System:

$$\frac{\text{BF} \times 8000}{1.2 \times 8000} = 2.96$$

BF = 3.5

CAD then modified the 3.5 factor to 3.0 based on qualitative judgements relative to tubing wall thickness. They reasoned that except for very small diameter tubing, the wall thickness of 8000-psi tubing was approximately twice that of 3000-psi tubing and so provided a more rugged part with respect to the following:

• Improved quality control of tubing material	Pin hole possibilities reduced
• Improved quality of tubing bends	Less ovality and wrinkling
• Improved quality of attachment of permanent end connectors	Less cold working of material, smaller heat-affected zone
• Easier handling prior to installation	Small dents and scratches not catastrophic
• Easier installation in vehicle	Removable end connectors less sensitive to misalignment, more gripping material available
	Permanent end connectors, more readily swaged, welded, or brazed
• Less affected by installed environment	More resistant to vibration
	More rugged with regard to nicks, chafing, etc.

CAD used Figure 11 to explain that tubing designed for 3000 psi using BF = 4 results in a 0.012-in. wall. This is not a suitable thickness from the standpoint of handling, so a 0.020-in. wall would probably be specified, resulting in a BF of 6.7. Using a BF of 3 at 8000 psi gives a 0.025-in. wall tube; this is satisfactory for handling and efficient stress-wise. Figure 11 indicates that at lower operating pressure levels, e.g., 1000 psi, large factors of safety are required to design tubing that is rugged enough for handling. This unwanted effect disappears at 8000 psi.

CAD noted that manufacturers of earthmoving equipment such as Caterpiller tractors, currently use BF=3 in systems operating at 3000 to 6000 psi. Their tubing is generally made from low carbon steel; this results in heavier walls than would be obtained with higher strength steels. Table 11, taken from an SAE handbook, gives working pressures for tubing made from mild steel using a BF of 3 (Reference 39).

[39] TUBE, PIPE, HOSE, AND LUBRICATION FITTINGS, Handbook Supplement HS 150, Society of Automotive Engineers, Inc., 1976 Edition.

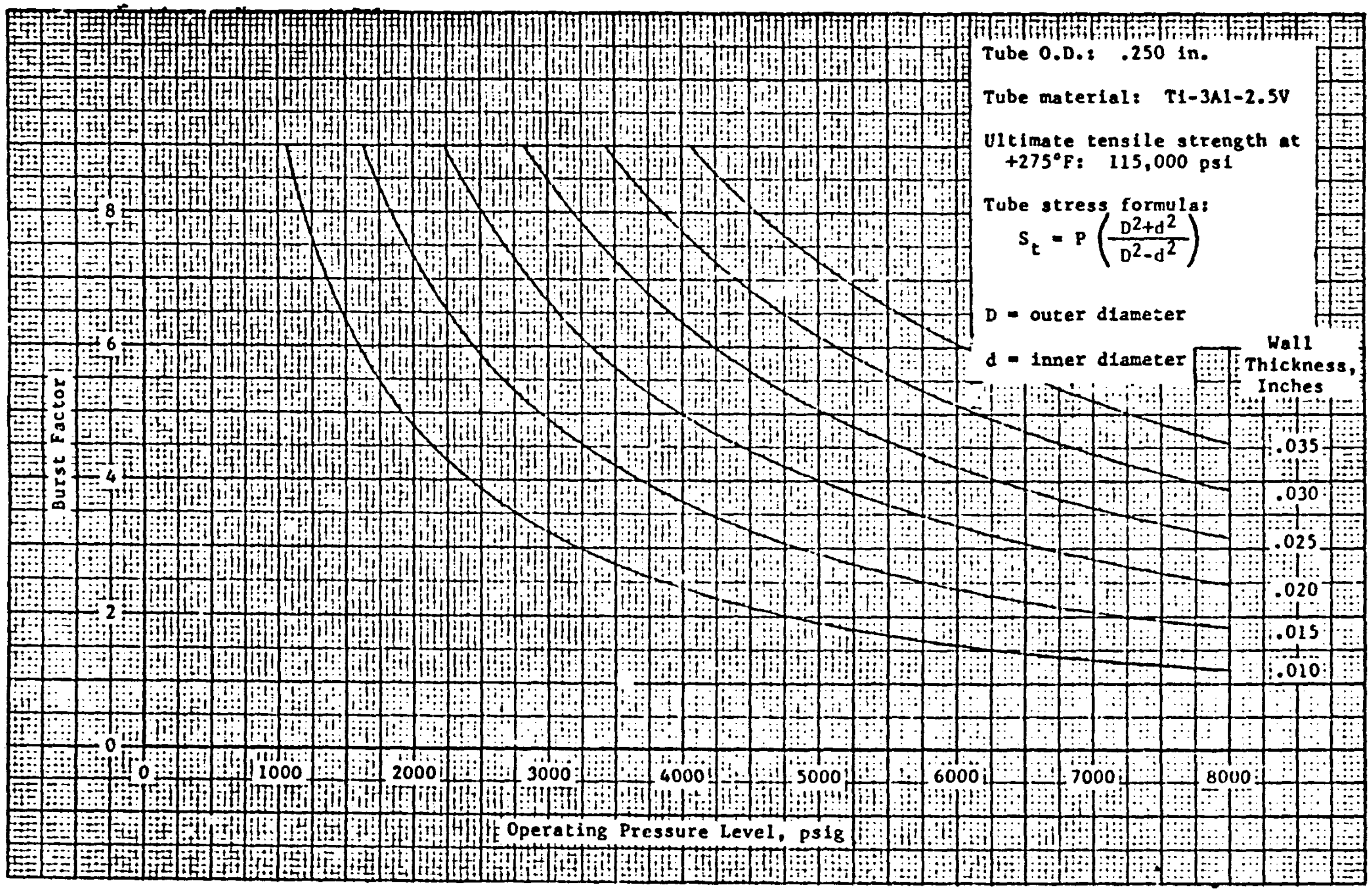

Figure 11. Burst Factors for -4 Size Titanium Tubing.

TABLE 11. REFERENCE WORKING PRESSURES FOR BF = 3.

REFERENCE WORKING PRESSURES AT APPROXIMATELY 3:1 DESIGN FACTOR, PSI

Nominal Tube OD, in		See Note*	Nominal Tube Wall Thickness, in 0.028	0.035	0.049	0.065	0.083	0.095	0.109	0.120	0.134	0.148	0.156
1/8	0.125	1	7600	9500									
		2	9300	12250									
		3	9050	11500									
3/16	0.188	1	5100	6350									
		2	5750	7450									
		3	5800	7400									
1/4	0.250	1	3800	4750	6650	8850							
		2	4200	5350	7900	11150							
		3	4200	5400	7800	10650							
5/16	0.312	1	3050	3800	5350	7050							
		2	3300	4200	6100	8500							
		3	3300	4200	6100	8350							
3/8	0.375	1	2550	3150	4450	5900	7550	8600					
		2	2700	3450	4950	6850	9150	10800					
		3	2750	3450	5000	6850	8950	10350					
1/2	0.500	1		2400	3350	4400	5650	6450	7400	8150			
		2		2500	3600	4950	6500	7600	9000	10100			
		3		2550	3650	4950	6500	7550	8800	9750			
5/8	0.625	1		1900	2650	3550	4500	5150	5950	6550			
		2		2000	2850	3850	5050	5900	6900	7700			
		3		2000	2900	3900	5100	5900	6900	7650			
3/4	0.750	1		1600	2200	2950	3750	4300	4950	5450			
		2		1650	2350	3150	4150	4800	5400	6250			
		3		1650	2350	3200	4150	4850	5400	6250			
7/8	0.875	1		1350	1900	2550	3250	3700	4250	4650			
		2		1400	2000	2700	3500	4050	4700	5250			
		3		1400	2000	2700	3500	4100	4750	5250			
1	1.000	1		1200	1650	2200	2800	3250	3700	4100	4550	5050	
		2		1200	1750	2350	3000	3500	4050	4500	5100	5700	
		3		1250	1750	2350	3050	3550	4100	4550	5150	5750	
1-1/8	1.125	1			1500	1950	2500	2850	3300	3650	4050	4450	
		2			1550	2050	2650	3100	3550	3950	4500	5000	
		3			1550	2100	2700	3100	3600	4000	4500	5050	
1-1/4	1.250	1			1350	1750	2250	2600	2950	3250	3650	4050	4250
		2			1400	1850	2400	2750	3200	3550	4000	4450	4700
		3			1400	1850	2400	2800	3200	3550	4000	4500	4750
1-1/2	1.500	1				1450	1900	2150	2450	2700	3050	3350	3550
		2				1550	1950	2250	2600	2900	3250	3650	3850
		3				1550	2000	2300	2650	2950	3300	3700	3900
1-3/4	1.750	1				1250	1600	1850	2100	2350	2600	2900	3050
		2				1300	1700	1950	2250	2450	2750	3100	3250
		3				1300	1700	1950	2250	2500	2800	3100	3300
2	2.000	1				1100	1400	1600	1850	2050	2300	2500	2650
		2				1150	1450	1700	1950	2150	2400	2650	2850
		3				1150	1450	1700	1950	2150	2450	2700	2850
2-1/4	2.250	1				975	1250	1450	1650	1800	2000	2250	2350
		2				1000	1300	1500	1700	1900	2150	2350	2500
		3				1000	1300	1500	1750	1900	2150	2400	2500

NOTE:
WALL THICKNESSES HAVING VALUES SHOWN TO RIGHT OF BOLD LINE ARE NOT NORMALLY CONSIDERED SUITABLE FOR 37 DEG SINGLE FLARING TO SAE J533.

*Pressure values listed opposite numbers 1, 2, and 3 for each tube OD were derived from the Barlow, Boardman, and Lamé formulas, respectively, with 17,000 psi allowable stress factor.

A BF of 3.5 rather than 3.0 was used in this study. There was general agreement that the demonstrated 120% surge factor for VHP systems allowed a BF of 3.5. But Boeing Vertol Company experience has indicated that the benefits listed previously, i.e., improved tube wall quality control, bending quality control, easier installation, etc., are not quantifiable. Therefore, it was decided not to further reduce the burst factor from 3.5 to 3.0.

CURRENT VHP DEVELOPMENT STATUS

VHP studies and testing programs completed thus far are listed below (References 23 through 30).

PHASE	
I	Theoretical study of basic parameters
II	Dynamic response study
III	Dynamic response test of a mass-loaded actuator
IV	Application study of VHP to the F-14 airplane
V	Laboratory testing of VHP hardware
VI	Preparations for VHP hardware endurance testing
VII	VHP hardware endurance test
VIII	Preparations for flight testing a VHP system
IX (in progress)	Flight test of a VHP lateral control system in a T-2C airplane

Work completed on a related program involvin~ the use of 8000 psi in advanced flight control actuation systems is as follows: (References 31 through 34).

PHASE	
I	Feasibility study
II	Design and fabrication of a control-by-wire modular actuator
III	Laboratory testing of control-by-wire modular actuator
IV	Design and fabrication of a control-by-wire actuator for flight testing
V (in progress)	Preparations for flight-testing a control-by-wire directional system in a T-2C airplane

A symposium on the VHP and AFCAS programs, sponsored by the Naval Air Development Center (NADC), was held in June 1976 at Warminster, Pennsylvania. The three-day conference was attended by approximately 80 industry and government personnel. Formal presentations were made by 10 participants. VHP and AFCAS hardware performance were demonstrated in the NADC hydraulics laboratory. The symposium was concluded with a presentation outlining the VHP Advanced Development Plan.

One ultimate objective of the VHP program is to reduce the weight of hydraulic system components; a second objective is to reduce space requirements. A 30% weight savings and a 40% reduction in volume was achieved in the F-14 study (Reference 26) using a 3.0 BF. As a result of the potential weight-saving benefits of VHP systems, the NADC is proceeding toward future application of VHP technology to Navy aircraft.

HYDRAULIC SYSTEM EVALUATION METHODOLOGY

INTRODUCTION

The methodology described here will be used to evaluate the hydraulic flight control and hoist systems of a baseline system, plus its two conceptual derivatives (ACP and VHP). The hoist is included as a typical utility hydraulic system function. In each instance, both a qualitative and a quantitative evaluation will be performed, and only hydraulic system elements will be considered. The quantitative evaluation will allow a strict numerical comparison of the baseline, ACP, and VHP systems.

To conduct this evaluation it was necessary to develop a methodology by which the various comparative factors (performance, reliability, maintainability, safety, vulnerability, volume, cost, weight) could be quantified. The selected technique was to hold performance constant and evaluate all other factors via their basic parameters. Reliability is measured in failures/1000 FH, maintainability is measured in MMH/1000 FH, etc.

The VHP Development Requirements section of this report discusses specific areas of VHP technology that require further work. But there is nothing to indicate that, at maturity, VHP system reliability and safety will be significantly different than that of 3000 psi systems. The VHP evaluation in this report will not be based on the technology of today. It will be assumed that a similar system has been installed in one or more high-performance fixed-wing aircraft and is now being considered for a helicopter application. This is a realistic event sequence, since advanced concepts for hydraulic systems, such as increased pressure, have historically been pioneered on fixed-wing aircraft. In the case of VHP systems, the U.S. Navy has been the major developer and all Navy-funded studies and tests have been related to fixed-wing aircraft.

RELIABILITY EVALUATION METHODOLOGY

Basic failure rates for significant hydraulic system elements will be established using CH-47C field data from References 9 and 40. These rates will be summed to obtain a total failure rate for the baseline system (see Table 15). The same component rates will be applied to the two advanced (ACP and VHP) systems. Arbitrary improvements in reliability will not be assumed. However, there will be instances where reliability improvements can be identified. One instance would be where a component cycles a significantly different number of cycles per FH in one particular

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[40] CH-47-347 PRODUCT ASSURANCE OPERATIONAL EFFECTIVENESS AND COST ANALYSIS, Document D347-11001-1, Boeing Vertol Company.

system. Its reliability would be adjusted, but not necessarily in propor ion to the difference in cycling rate, since there are other factors that affect reliability.

The estimated component failure rates will not reflect non-environmental effects of field operations. Erroneous replacements and maintenance damage, not directly attributable to component design, will not be considered. For this reason, it should be recognized that the CH-47C system failure rate used here may fall somewhat short of that recorded elsewhere. But the technique used should minimize the effects of subjective or noninherent reliability modifiers.

MAINTAINABILITY EVALUATION METHODOLOGY

The end products of this evaluation will be a quantitative assessment of system MMH per 1000 FH and a qualitative assessment of maintainability strengths and weaknesses. Quantitative parameters for off-aircraft maintenance will not be analyzed in detail, because of the workload that would be required to obtain valid assessments. However, any basic design peculiarity that impacts off-aircraft maintenance will draw comment.

Corrective maintenance task times will be derived from a time analysis of the steps required to complete each task. These will be laboratory times. With practice, the average mechanic normally would be able to complete each task in the time allotted. In order to obtain realistic field task times, the laboratory times should be approximately doubled. For the purposes of this evaluation, however, no adjustment factor is required since the laboratory times will be used for evaluating all three hydraulic systems. It is expected that the following factors will have the greatest impact on corrective maintenance:

1. Component access
2. East of fault isolation
3. Requirements for depressurizing and repressurizing systems
4. Requirements for draining and refilling systems
5. Number and type of attaching bolts
6. Number and type of hose/tube connections
7. Number and type of electrical connectors
8. Number, type, and lubrication requirements of loose seals

9. Size and weight of components

10. Need for GSE or PGSE

11. Need for special skills

The corrective action maintenance burden for each system will be calculated by summing component maintenance burdens using the following formula:

$$\text{System Maintenance Burden} = \sum_{X=0}^{X \to n} \frac{(\text{MMH})}{(\text{Malfunction})} \frac{(\text{Malfunction})}{(1000\ \text{FH})}$$

Malfunctions/1000 FH will be obtained from the reliability assessment. System preventative MMH will be determined by:

$$\sum_{X=0}^{X \to n} = \frac{(\text{MMH})}{(\text{Inspection})} \frac{(\text{Inspections})}{(1000\ \text{FH})}$$

Preventive maintenance task times are expected to be closer to field times, as compared to corrective maintenance task times. Once again, no adjustment factor is required since the results will be used only to compare the three hydraulic systems. But note that the preventive/corrective MMH ratio for any given system will be distorted. The factors having the greatest impact on preventive maintenance are:

1. Inspection frequency

2. Servicing frequency

3. Need for depressurization to test or service

4. Size of area to be inspected

5. Component access

6. Need for GSE or PGSE to make checks

7. Features included in design such as sight gages versus dip sticks.

SAFETY EVALUATION METHODOLOGY

This evaluation will include a discussion of system safety plus a determination of the occurrence probability of a catastrophic accident. The qualitative analysis will cover potential hazards that could develop into a mishap situation. A portion of this

section will deal with the past history of the CH-47 system, or similar systems. This part of the two-fold evaluation will be more akin to traditional safety assessments. However, manpower constraints prohibit the accomplishment of a complete hazard analysis.

The second portion of this evaluation will quantify those failures that impact flight safety reliability (FSR). The analysis establishes catastrophic system failure probabilities which result in the loss of an aircraft. FSR rates differ from reliability failure rates in that a probability is assigned to the system component failing in a manner that could impair flight safety. In general, component FSR is lower than reliability failure rates, which include malfunctions such as loose, out-of-tolerance, bent, and worn components.

Figure 12 shows the mechanics of a FSR calculation. The diagram represents a flight control system from the point of hydraulic power takeoff (transmission accessory gearbox) through the entire system. Each block would normally contain the noun for a particular component and its FSR.

VULNERABILITY EVALUATION METHODOLOGY

This analysis will include a discussion of basic system characteristics and their impact on vulnerability. A quantitative assessment will determine the equivalent singly vulnerable area of the system. For a given threat scenario, a specific equivalent singly vulnerable area will result in a predetermined number of aircraft lost and damaged. Therefore, a direct comparison of these areas will provide a comparison of relative vulnerability.

Determining singly vulnerable area requires that the system "presented area" be first established. The system presented area for five views: front, back, left, right, and bottom must be calculated and averaged. All hydraulic system elements are considered. Shielding by structure or other aircraft components will not be considered. The same averaging process, using five views, is then used to calculate total aircraft presented area.

The concept of an equivalent singly vulnerable area is based on replacing redundant systems with a singly vulnerably equivalent and adding that area to the areas of system components that are actually nonredundant. Equivalency is based on the premise that a singly vulnerable system and the redundant system have the same helicopter kill probability for a given hit density. This process was defined and used in Reference 41.

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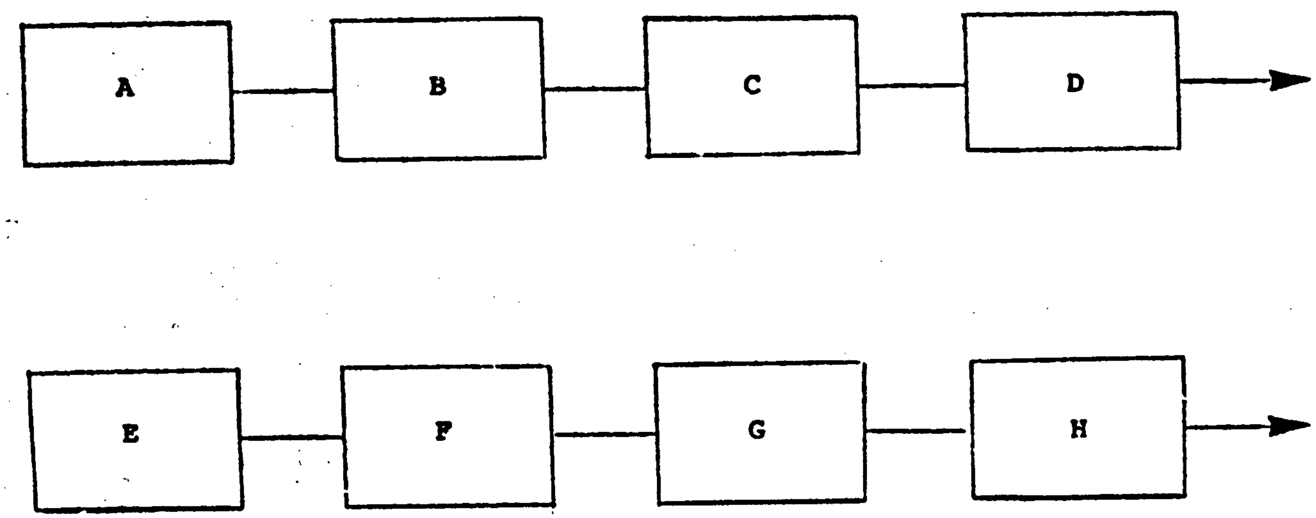
[41]Harding, D., and Doman, G., PROPOSAL FOR ARMORED AERIAL RECONNAISSANCE SYSTEM (AARS) VULNERABILITY STUDY, The Boeing Vertol Company; USAAMRDL Technical Report 73-57 A/B, Eustis Directorate, U. S. Army Air Mobility Reserach and Development Laboratory, Fort Eustis, VA, May 1974.



The Flight Safety Reliability (FSR) of the hydraulic system for a given time "t" is the probability (?) that both systems fail in the time interval t. FSR = 1-P (at least one system working in interval "t"), therefore, $FSR = \{1 - 1 - (R_A x R_B x R_C x R_D)(1 - R_E x R_F x R_G x R_H)\}$

Also: $FSR = e^{-\lambda t}$ therefore: $\lambda_{fs} = \frac{-\ln FSR}{t}$

λ_{fs} = Flight Safety Reliability

Figure 12. Flight Safety Evaluation Method.

The singly vulnerable area for redundant system components is then calculated using Figures 13 and 14 as follows:

1. Calculate the ratio of system component presented area over total aircraft presented area
2. Enter Figure 14 at this value.
3. Intercept the curve for the number of hits being considered and read the kill probability value.
4. Enter Figure 15 with this value and intercept the curve for the same number of hits that was used previously.
5. Read ratio ordinate.
6. Multiply this value by aircraft area to obtain the equivalent singly vulnerable area of the system.

The equivalent vulnerable area resulting from inadequate separation of redundant systems must be added to the area that was obtained by use of Figures 13 and 14. Analysis of the probability of killing both systems with a single hit (given that one system is hit) can be geometrically generated by projecting projectile paths against pairs of lines with a given spacing. Probability of killing both systems, given a hit on one, is obtained by dividing the possible vectors intercepting both by total possible vectors in the lower hemisphere. Results for a 7.62 mm threat are shown in Figure 15. The probability of a kill due to inadequate system element separation, as determined from Figure 15, is then multiplied by the presented area of those elements.

Figure 14 Composition

Figure 14 is a plot of the equation:

$$P_K = 1-2\left(1-\frac{Av}{Ap}\right)^N + \left(1-2\frac{Av}{Ap}\right)^N$$

where: P_K = Probability of killing both systems of a redundant pair of vulnerable systems having the total vulnerable area (A_V)

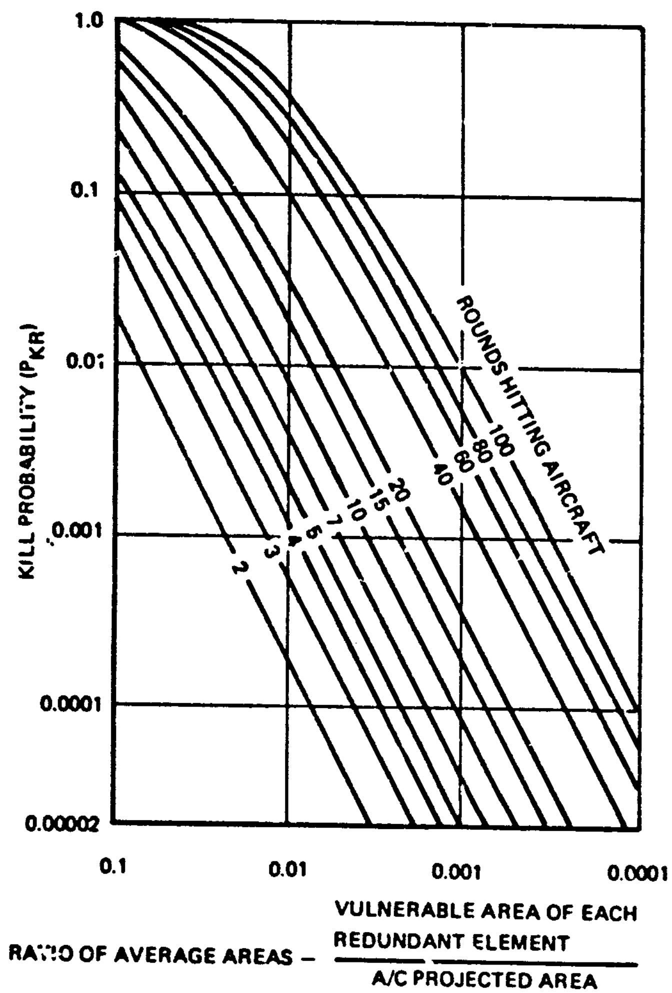


Figure 13. Kill Probability of Multiply Vulnerable Components

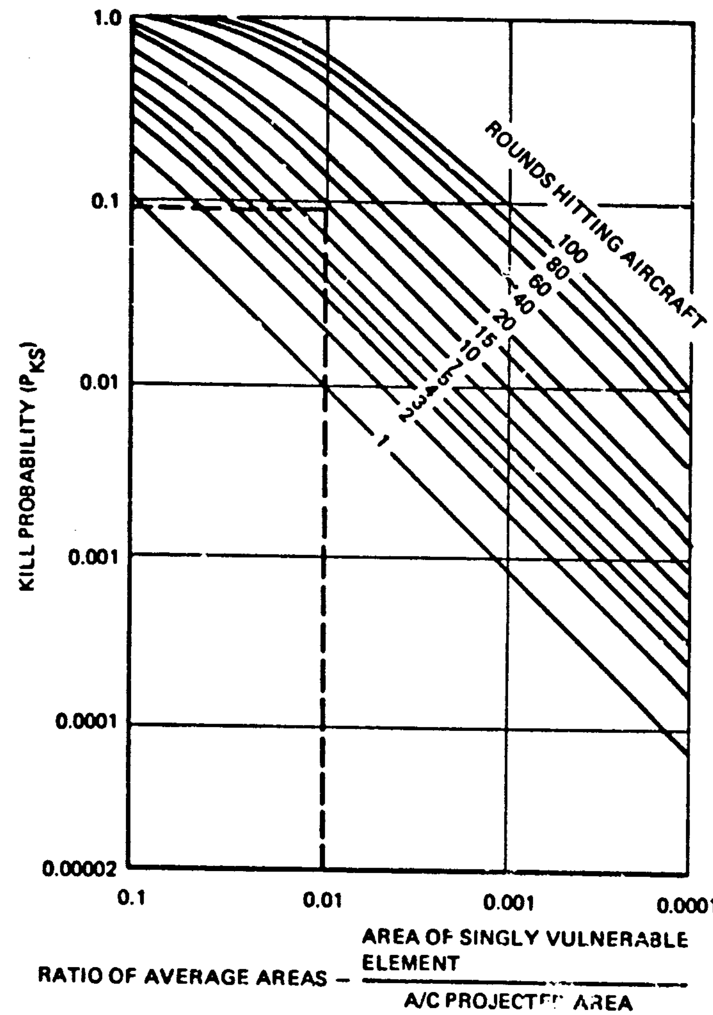


Figure 14. Kill Probabili y of Singly Vulnerable Components.

A_V = Vulnerable area of each pair of redundant systems

A_p = Total presented area of the aircraft

N = Number of projectiles striking the aircraft.

This equation is a standard tool used in vulnerability analysis and is based on probability theory.

Figure 14 Composi...

Figure 14 is a plot of the equation:

$$P_K = 1-(1-\frac{A_{VS}}{A_p})^N$$

where:

P_K = Probability of kill

A_{VS} = Vulnerable area of system

A_p = A/C Presented Area

N = Number of rounds striking the aircraft

This equation is another standard tool that is used in vulnerability analysis. Basically, it is the standard probability distribution for a binary distributed random variable.

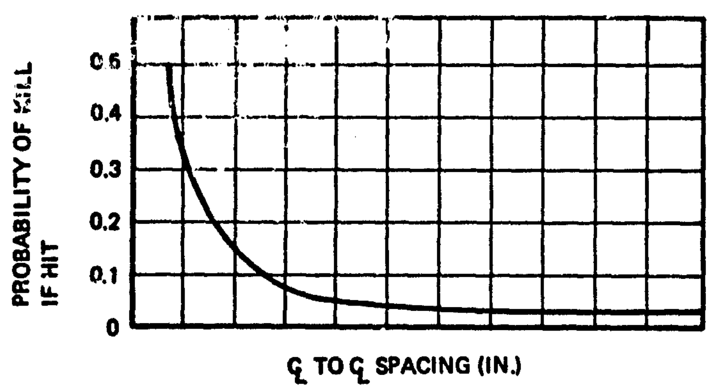


Figure 15. Probability of a Dual System Kill as a Function of Hydraulic Element Spacing.

VOLUME EVALUATION METHODOLOGY

The state-of-the-art section of this report noted that in the past, hydraulic system volume has had only a negligible effect on airframe envelope. While factors such as modularization

and advanced technology transmissions may change this somewhat, fuselage envelope trade-offs would probably minimize any end effects. For example, increasing the fuselage envelope in the area of the swashplate actuator might allow relocation of another component to that area and subsequently reduce the fuselage envelope elsewhere. For these reasons, at least initially, no attempt will be made to analyze volume in detail. Total system volume will be observed for deviations from tradition, but only unusually large volumes will be calculated and documented.

COST EVALUATION METHODOLOGY

The initial objective of this task was to determine total LCC for the various hydraulic systems under consideration. During the state-of-the-art cost investigation, it was concluded that LCC was too complex a subject to use standard costing tools without extensive further investigation. Probably the most important consideration involving cost is the degree and configuration of systems modularization. Using present costing methods to determine LCC, without expending time to analyze all of the implications associated with modularization, could easily result in distorted system comparisons. Therefore, this methodology section will deal with design-development and acquisition costs, but not operational costs.

Design-development and acquisition costs will be presented in nondimensional parameters. Systems will be rated on a one-to-ten basis, with one being the lowest cost and ten the highest. The baseline system will be rated as five in each category, while the ACP and VHP systems will be rated higher or lower, depending on the evaluation team's judgement.

Evaluation factors will include complexity of design, unusual qualification test requirements, size of component, number of machining operations required, and use of advanced materials. While the results of this particular evaluation technique must be considered approximate at best, it should display the general relationship between systems.

WEIGHT EVALUATION METHODOLOGY

System weight will be determined in a number of ways. Where possible, known component weights, or the weights of similar components, will be used. If necessary, trending techniques will be employed. Factors will be applied to the known weights of recently developed components; these factors will consider such characteristics as complexity and application. The weight-estimating techniques employed will be

those used by most aerospace companies. Where factors are applied, the rationale for selecting the factor will be explained. Figure 16 provides an overview of the methodology that will be employed.

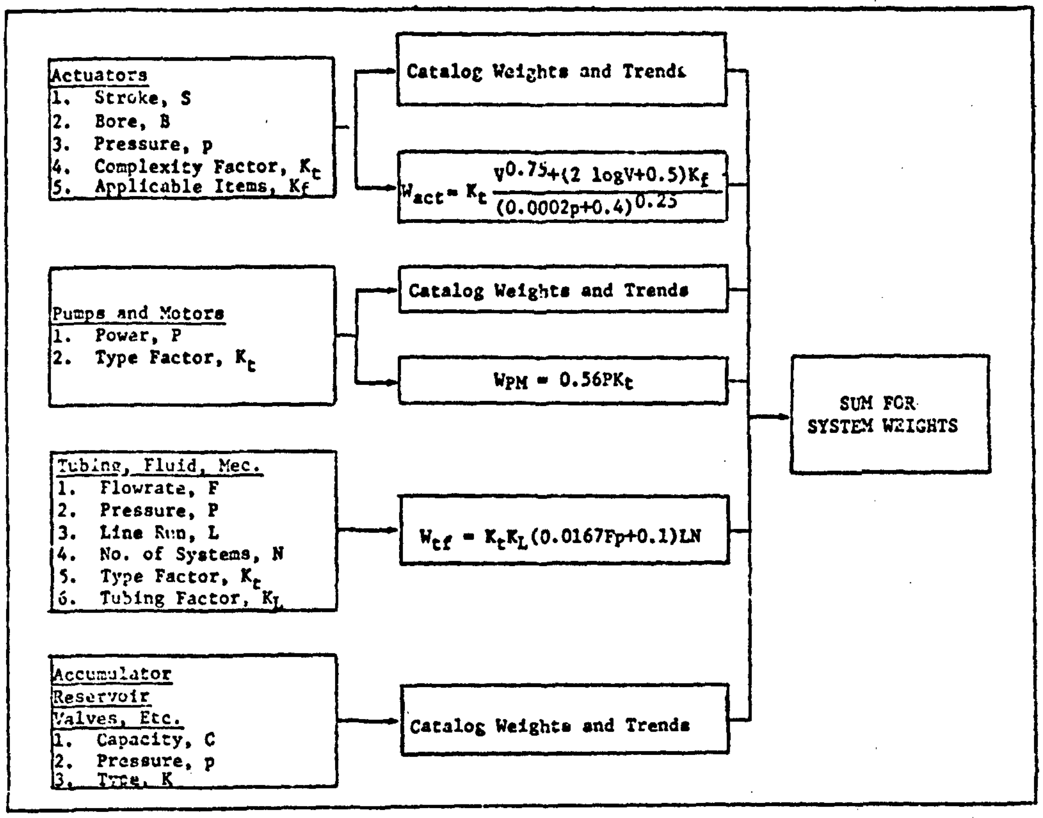


Figure 16. Weight Evaluation Methods.

The factors K_t and K_f have been obtained from the Reference 42 report.

[42] York, R.A., FLYWEIGHT ACTUATORS, AN EVALUATION OF THE WEIGHT OF AIRCRAFT HYDRAULIC ACTUATORS, Presented before the Seventy-Third Meeting of the Society of Automotive Engineers' A-6 Committee, October 16-20, 1972.

SYSTEM DESCRIPTIONS

DESIGN GUIDELINES

The CH-47C was selected as the baseline system. The selection process is described in Appendix D. The guidelines and assumptions that were employed to define the two advanced systems are as follows:

1. The CH-47C baseline system performance capabilities shall remain virtually unchanged.
2. The conceptual configurations are designed in general accordance with the Type II, +275°F systems defined in MIL-H-5440.
3. Existing upper control actuator rates, stroke lengths, and output force shall be maintained.
4. Modification of transmissions for pump drive pads is acceptable.
5. 8000-psi system lines will provide the same percentage pressure drop as their equivalent 3000-psi system line. The 8000-psi system line ΔP will therefore be 8/3 that of the calculated line ΔP for the equivalent 3000-psi system line. New lines will be sized for a maximum fluid velocity of 25 ft/sec.
6. Tubing wall thickness for 8000-psi lines will be determined using a burst pressure of 3.5 x 8000 = 28,000 psi. Wall thickness of return pressure lines shall be determined using a burst value of 3.5 x 4000 = 14,000 psi. Suction line wall thickness will be sized for a burst pressure of 3.5 x 600 = 2,100 psi.
7. VHP pressure design factors will be as follows:

	Lines and Fittings	Components
Maximum surge pressure	1.20	1.20
Proof pressure	1.50	1.50
Burst pressure	3.50	2.20

8. 8000-psi components are approximately 20% heavier than 3000 psi components with the same flow rate (Reference 24).

9. Modularizing components increases the weight of components depending on modularization efficiency. A 15% increase in weight will be assumed.

10. Flexible hose weights for 8000-psi lines will be based on existing 6000- and 8000-psi hoses. Catalog weights shall be used for low pressure hose. 50% of the hoses will have scuff guards.

11. Information covering 8000-psi pumps will be based on data generated by a pump manufacturer who participated in the Rockwell 8000-psi system development program (Abex Corporation).

12. Permanent and separable connector weights will be based on actual weights of mechanically swaged fittings currently used in 3000/4000-psi systems. Weights shall be increased by 10% for 8000-psi usage.

BASELINE SYSTEM DESCRIPTION

General Description

The CH-47C Chinook is a twin-turbine, tandem-rotor helicopter designed to provide air mobility of troops, weapons, vehicles, equipment, and supplies. It is designed for continued operation under relatively primitive conditions, such as unimproved terrain and extremes of weather conditions, with a minimum of ground support equipment. Figure 17 shows the overall dimensions of the CH-47C helicopter, while Table 12 shows its weight and performance characteristics. Figure 18 provides details of the various fuselage areas.

Flight control systems are fully powered by dual hydraulic systems and include dual SAS. Dual flight controls and instrumentation are provided in the cockpit. The lower control system uses push-pull rods with mechanical mixing, and includes trim and stick positioning.

A utility hydraulic system is provided for operation of the ramp, wheel brakes, cargo hook release, and rescue winch. Electrical power is provided by two 20-kva air-cooled alternators. All hydraulic pumps and generators are driven through an accessory gearbox mounted on the aft transmission. Power for starting the engines and ground checkout of systems is provided by a gas turbine APU mounted in the aft pylon.

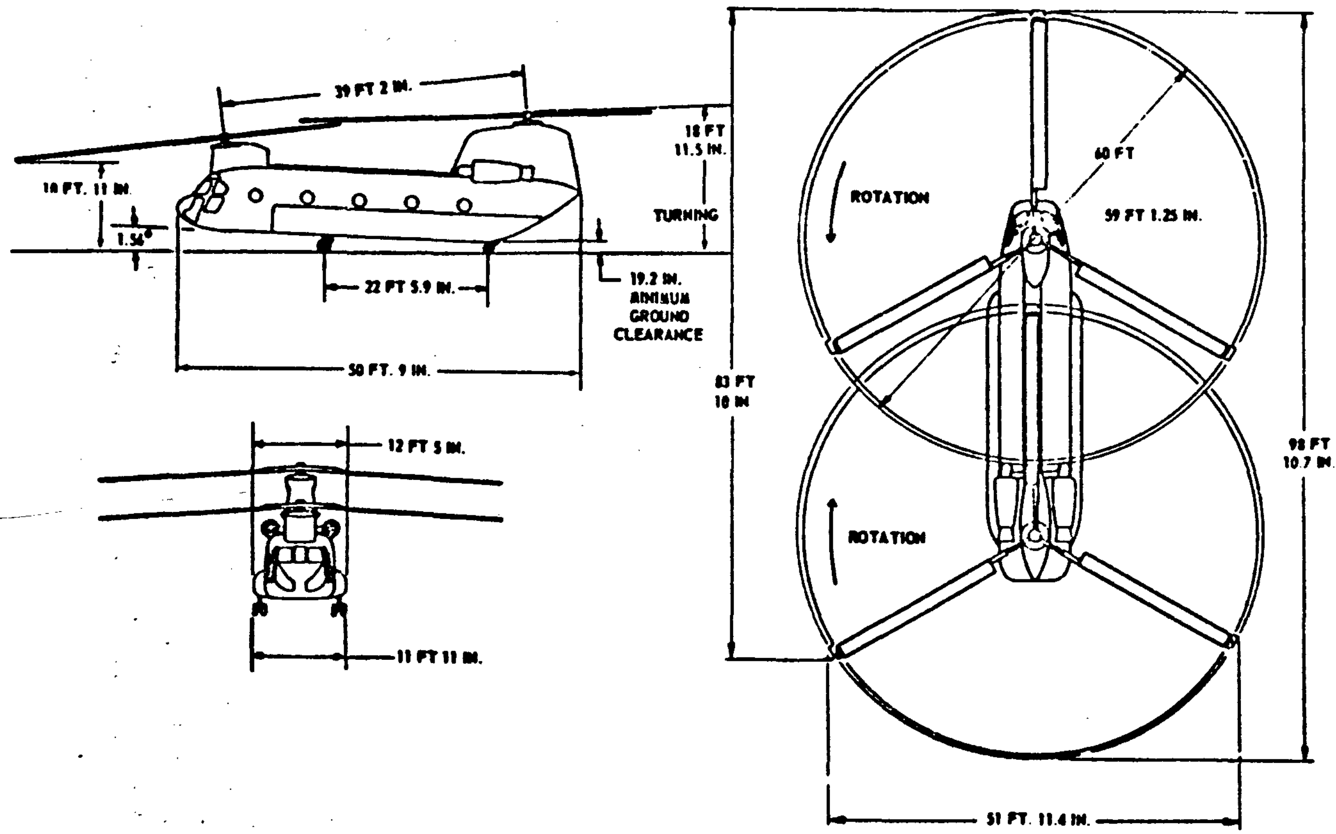


Figure 17. CH-47C Overall Dimensions.

TABLE 12. CH-47C WEIGHT AND PERFORMANCE

	CONDITION 1	CONDITION 2	CONDITION 3
TAKE OFF WEIGHT	39,200 lb	33,000 lb	46,000 lb
WEIGHT EMPTY	20,616 lb	20,616 lb	20,785 lb
PAYLOAD	13,212 lb	7,262 lb	23,212 lb
MISSION RADIUS	100 nm	100 nm	20 nm
AVERAGE CRUISING SPEED	139 kn	137 kn	114 kn
MAXIMUM SPEED AT SEA LEVEL (NORMAL RATED POWER)	156 kn	164 kn	123 kn
MAXIMUM RATE OF CLIMB (SEA LEVEL, STD TEMP, NORMAL RATED POWER)	2,045 ft/min	2,880 ft/min	1,320 ft/min
HOVER CEILING, OUT OF GND EFFECT (MAX POWER, STD TEMP)	9,600 ft	14,750 ft	SEA LEVEL
SERVICE CEILING (NORMAL RATED POWER, STD TEMP)	10,200 ft	15,000 ft	8,000 ft
MAX FERRY RANGE (INTEGRAL X INTERNAL AUX FUEL ONLY; CRUISE AT OPTIMUM ALTITUDE AND STD TEMP; NO PAYLOAD; 10% FUEL RESERVE)			1,224 nm

<u>CONDITION 1 CRITERIA:</u> Takeoff gross weight equals gross weight to hover out of ground effect at 6,000 ft/95°F. Radius of action of 100 nm. Payload is carried internally.

<u>CONDITION 2 CRITERIA:</u> Takeoff gross weight equals design gross weight. Radius of action of 100 nm. Fuel reserve of 10%. Payload is carried internally.

<u>CONDITION 3 CRITERIA:</u> Takeoff gross weight equals alternative design gross weight. Radius of action of 20 nm. Fuel reserve of 10%. Payload is carried externally. Except for the mission average cruise speed, all other performance is predicated on internal loading of cargo.

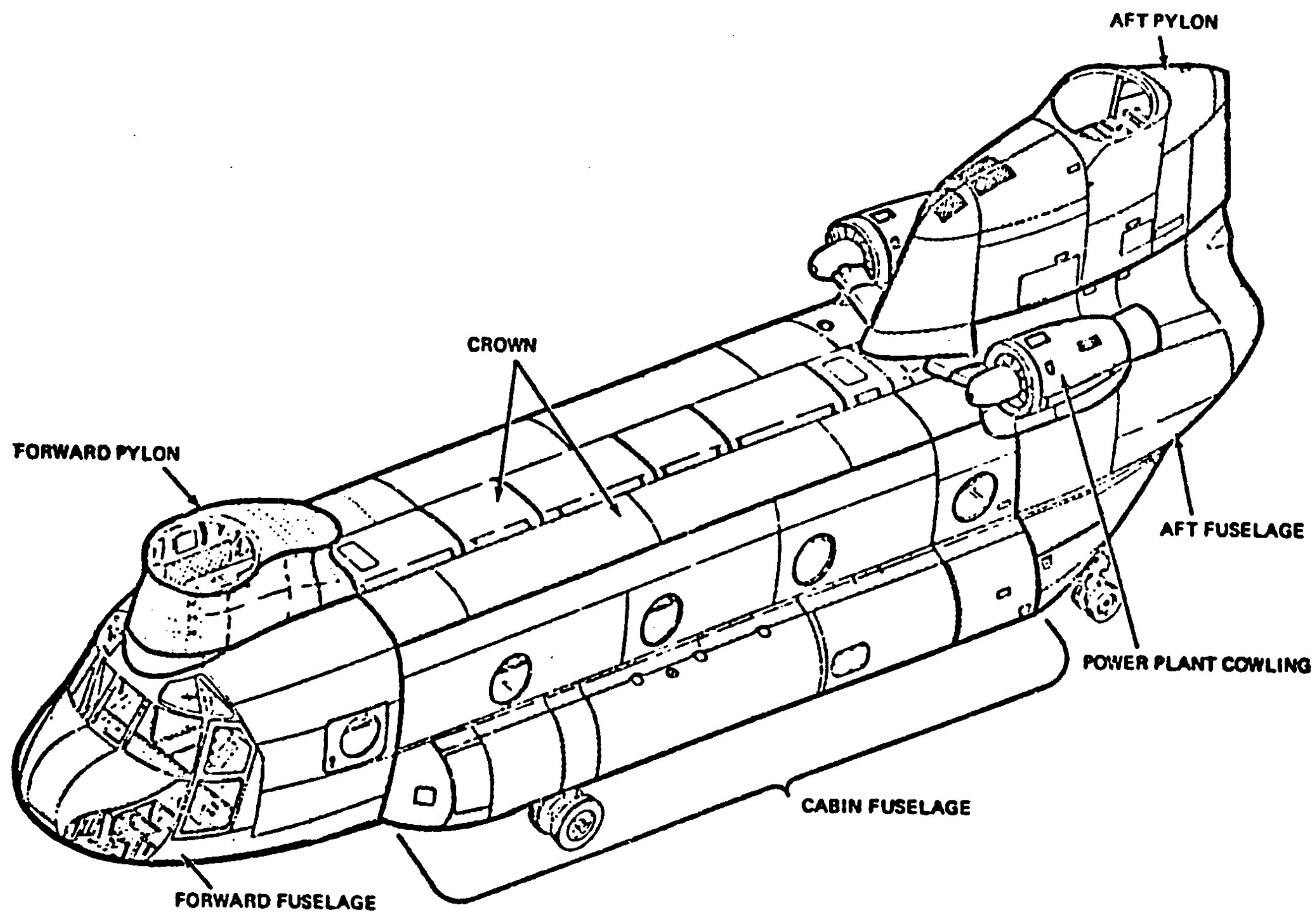


Figure 18. CH-47C: Seven Major Airframe Areas.

In order to be self-sustaining in the field, the Chinook incorporates design features such as integral work platforms, steps, and a portable maintenance crane which may be mounted on the airframe to remove and install large components.

A compartment behind the copilot (left-hand seat) is called the "lower controls closet", and it contains the lower control stick boost and SAS actuators. A similar compartment on the opposite side (behind the pilot's seat) is called the "heater closet" area; the rescue hoist system is located there.

The forward pylon is a faired structure that surrounds the upper portion of the forward rotor transmission and the rotor controls. Two upper rotor control hydraulic actuators are located in this area, one on each side of the transmission. One large integral work platform on each side of the forward pylon provides access to the hydraulic actuators, rotor controls, and transmission.

The cabin crown area is the skin and structure that forms the top of the fuselage. Fairings form a tunnel atop the cabin crown and house flight control rods, hydraulic lines, electrical cables, and the transmission drive shaft. A walkway is provided adjacent to the tunnel on the right-hand side.

The aft fuselage area contains the hydraulically operated cargo ramp and door. Most of the utility hydraulic system plumbing, including the ramp control, is located in this area; the majority of it on the right-hand wall of the fuselage. The auxiliary power unit and its hydraulic motor/pump are located in the upper rear portion of the aft fuselage area.

The combining transmission and the aft rotor transmission are located in the aft pylon area. Rotor controls and hydraulic actuators, similar to those in the forward pylon, are located around the aft transmission. Integral work platforms provide access to components located in the aft pylon. The lower portion of the aft transmission contains an accessory gearbox (AGB). This section protrudes into the aft fuselage area and access to it is from inside the fuselage. Both flight control hydraulic pumps as well as the utility hydraulic pump are located on, and driven by, the AGB.

Flight Control Hydraulic System

The flight control hydraulic system consists of two identical 3000-psi independent systems designed to the specifications of MIL-H-5440. Each system contains its own hydraulic tank, pump, valves, filters, fittings, and actuators. Each system supplies hydraulic pressure to operate the forward and aft pivoting and swivelling (upper rotor control) dual actuating

cylinders, the SAS dual extensible links, and the (lower control) dual stick-boost actuators. Figure 19 is a schematic diagram of the CH-47C flight control system. Figure 20 shows the major actuators powered by the flight control hydraulic system.

The CH-47C has pressurized pump-inlet flight boost systems. Air is taken from the No. 2 engine compressor and directed to a manifold where the air is filtered, pressure-regulated, and then directed to each flight boost hydraulic tank.

MIL-H-5606 hydraulic fluid from the tank is fed to the pump, where the fluid is pressurized to 3000 psi and then directed to the flight control manifold where it passes through a filter to a pressure relief valve and a solenoid-operated ON/OFF control valve. Fluid from the manifold is directed to the forward and aft pivoting and swiveling dual actuating cylinders. At the same time, it is directed through a filter, and a 1500-psi pressure reducer, to the SAS solenoid control valves and to the dual stick-boost actuating cylinder manifolds, where passages direct the fluid to the actuating cylinders. The fluid is returned from the cylinders through a filter to the hydraulic tank. The pivoting and swiveling dual upper actuating cylinders and the dual stick-boost actuators are capable of normal operation even when powered by only one hydraulic system. The dual extensible links consist of two actuators which are bolted together end-to-end. The No. 1 hydraulic system supplies fluid to the lower actuators and the No. 2 system supplies fluid to the upper actuators. When both hydraulic systems are functioning, each actuator provides one-half of the total motion required. If one hydraulic system fails, the associated actuator locks in a fixed dimension. The other actuator then automatically provides the full motion required. Table 13 shows CH-47C actuator design features.

Corrosion resistant steel tubing and steel MS flareless fittings are used in all 3000-psi circuits. Aluminum is used for 1500-psi and return line plumbing.

Utility Hydraulic System

The utility hydraulic system consists of APU start, engine start, and hydraulic power systems, and the related subsystems. Accumulator pressure is used to start the APU by means of a motor-pump. With the APU operating, the utility hydraulic pump is driven by the AGB, which is driven by the AGB motor using fluid power from the APU motor-pump. During operation, the utility hydraulic pump repressurizes the accumulator for the next APU start. Utility pump pressure can be used by the engine start system or the utility subsystems. Figure 21 shows a simplified block diagram of the utility hydraulic system.

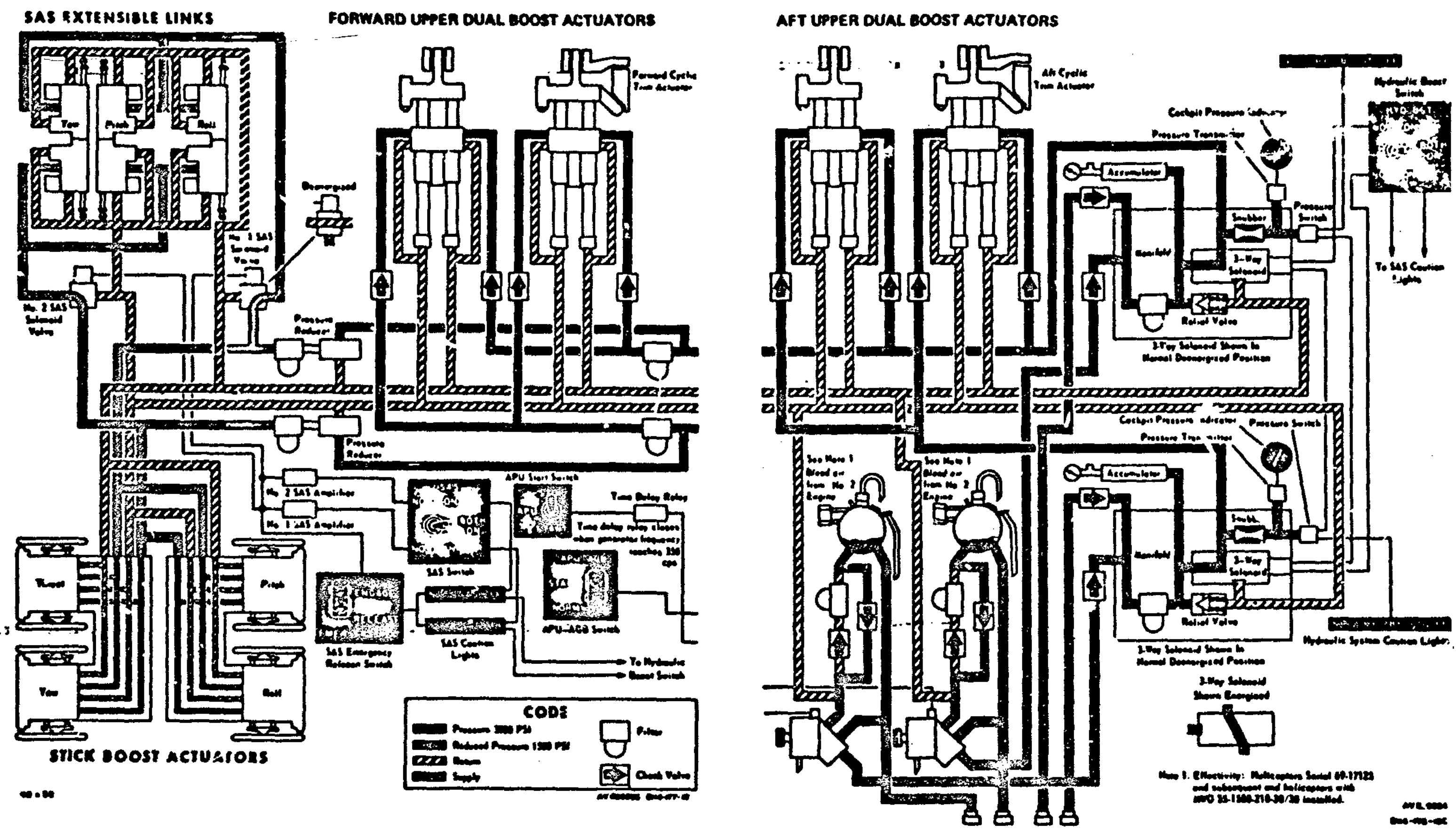


Figure 19. CH-47 Flight Control System.

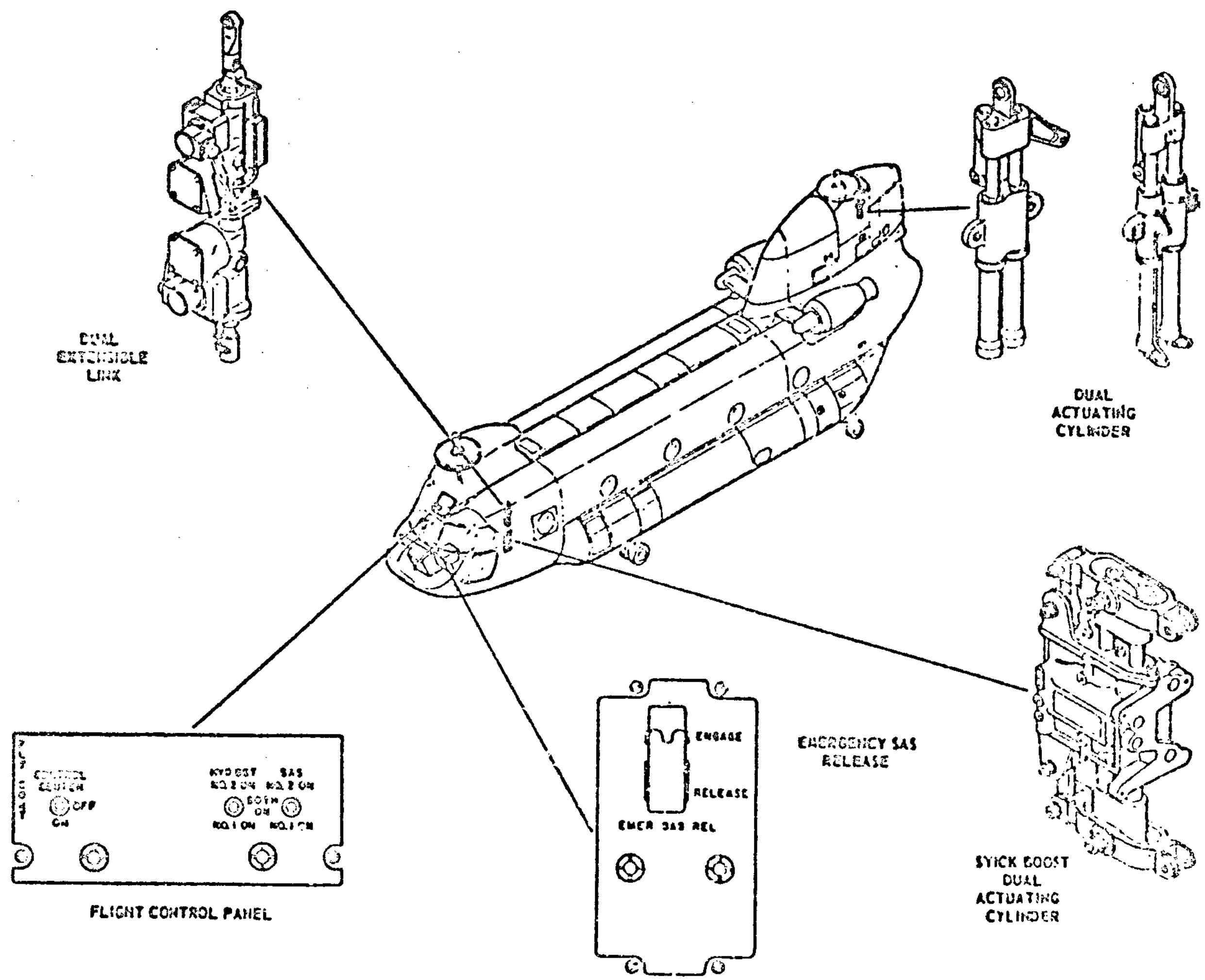


Figure 20. CH-47 Major Actuators Powered by Flight Control Hydraulic System.

TABLE 13. DESIGN FEATURES OF BASELINE ACTUATORS

	STICK-BOOST ACTUATOR	SAS ACTUATOR	UPPER CONTROL ACTUATORS SWIVELING	UPPER CONTROL ACTUATORS PIVOTING
ACTUATOR TYPE	DUAL PARALLEL	BACK-TO-BACK SINGLE ACTRS W/INTERNAL LOCK	DUAL PARALLEL	
QTY PER SYSTEM	4	3	2	2
OPERATING PRESSURE PSI	1500	1500	3000	
NET AREA IN.^{2} PER SYS				
EXTEND	.236	.386	.7516	.7516
RETRACT	.236	.386	1.7955	1.8661
ACTUATOR LOAD CAPABILITY - LB PER SYSTEM EXTEND	177	579	3132	3342
RETRACT	177	579	2255	2255
STROKE - IN.	±2.25	±.17, ±.22, ±.34	±6.25	
RATED FLOW - GPM (MAX) PER SYSTEM	.441	.425	VALVE FLOW ACTR. FLOW	3.59 2.13
STEADY STATE FLOW - GPM	.043	.10	.33	
VALVE TYPE	MANUAL DUAL TANDEM 4-WAY SPOOL AND SLEEVE VALVE	SINGLE ELECTRO-HYDRAULIC 4-WAY SERVO VALVE	HYDROMECHANICAL TANDEM 3-WAY SPOOL AND SLEEVE VALVE	
ACTUATOR GAIN - OPEN LOOP - RAD/SEC IN./SEC	120	3.6 @ 150#	60	
PISTON VELOCITY - IN./SEC (MAX) EXTEND	7.2	4.2	7.9	7.4
RETRACT	7.2	4.2	10.9	10.9
WEIGHT - LB MAX	7.0 EA	11.1 EA	37.0 EA	60.3 EA

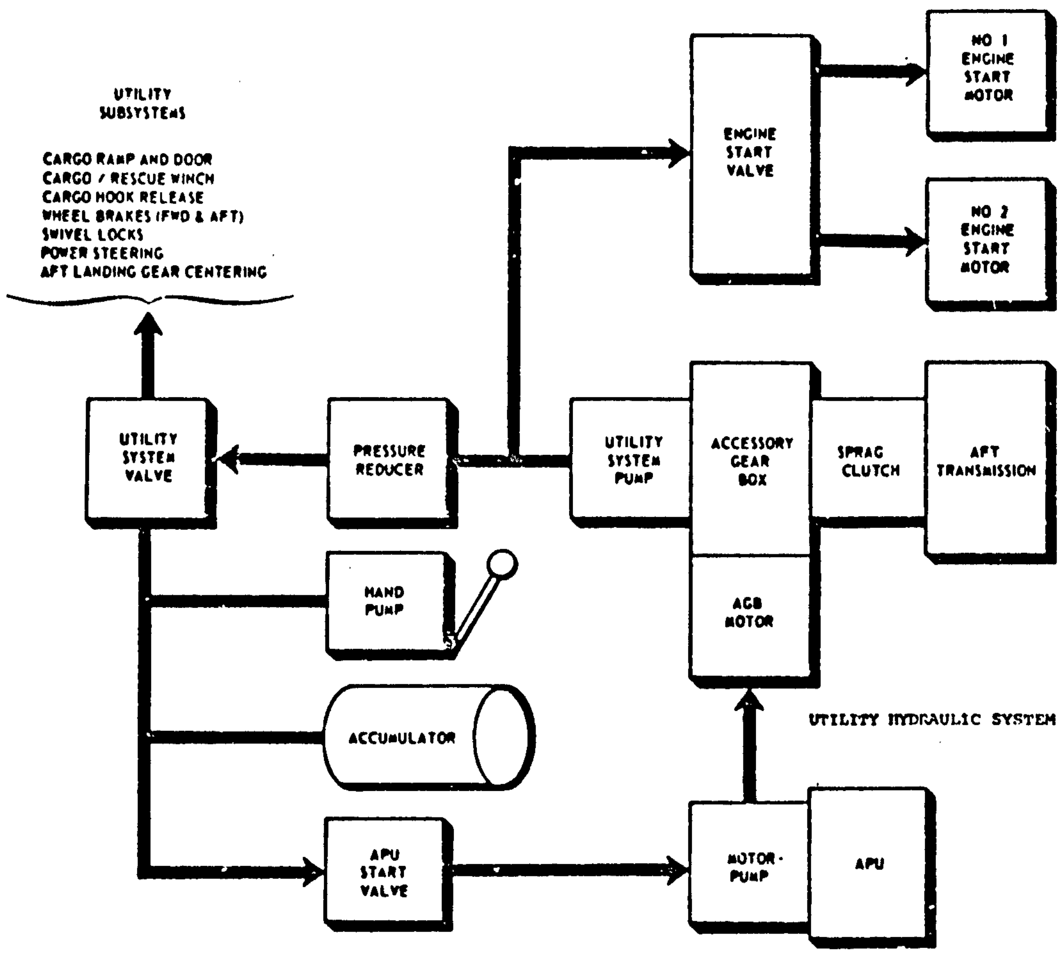


Figure 21. Block Diagram of CH-47 Utility Hydraulic System.

The subsystems that are operated by the utility system are: aft landing gear centering, power steering, swivel locks, wheel brakes, cargo hook, cargo/rescue winch, and cargo ramp and door. Figure 22 is a schematic diagram of the CH-47 utility hydraulic system and the subsystems it powers.

Utility Hydraulic Subsystems

The cargo ramp is operated hydraulically and can be stopped and held at any intermediate position. A retractable door is an integral part of the ramp. When the ramp is being lowered, a sequence valve causes the door to retract automatically into the ramp. When the ramp is being raised, the valve causes the door to extend. A manually-controlled locking pin on the sequence valve permits the ramp to be raised and lowered with the door fully retracted. The ramp can also be operated when normal system pressure is not available, by pressurizing the system accumulator with a hand pump.

The forward and aft wheel brakes are operated simultaneously when the aft landing gear is centered, swivel locks engaged, and the brake pedals depressed. Aft landing gear centering is accomplished hydraulically when swivels are locked. Parking brakes are applied to the forward and aft wheels. The pilot and copilot master cylinders are isolated from each other by brake transfer valves.

The external cargo hook system is not related to the rescue hoist system. The external hook is hydraulically released and re-engaged pneumatically. If utility hydraulic system pressure fails, the hook can be released pneumatically. An emergency manual release is also provided for the cargo hook.

The cargo/rescue winch is a hydraulically-driven, level-winding reel with an automatic brake. The brake is released hydraulically when winch operation is selected. Winch speed and direction is controlled by a solenoid valve and rheostats at the pilot's control panel and hoist operator's position. Maximum reel-out speed is limited by flow regulation.

For the purposes of this study, the winch system is assumed to have no cargo moving capability, and the present need for rigging the cable before rescue system operation is not considered. In addition, in order to more accurately represent modern hoist systems, the system performance was uprated as shown in Table 14.

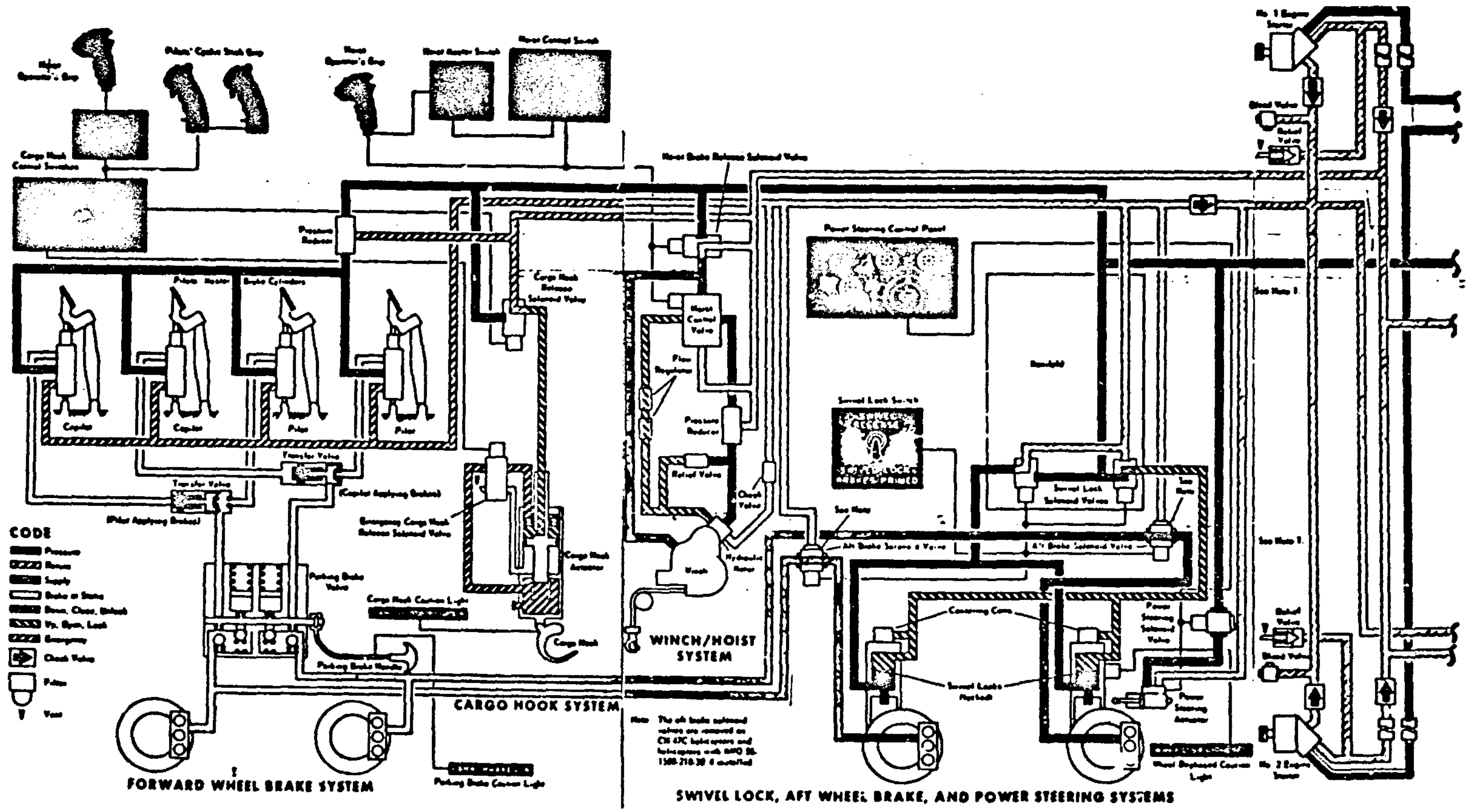


Figure 22. CH-47 Utility Hydraulic System and Subsystem.

TABLE 14. PRODUCTION HOIST SYSTEM COMPARED TO IMPROVED SYSTEM		
PARAMETER	SYSTEM	
	PRODUCTION	IMPROVED
Load Capability	600 lb	600 lb
Cable Reel-in Speed	100 ft/min	300 ft/min
Cable Length*	200 ft	250 ft
System Flow	3 gpm	6 gpm**

* Does not impact study since winch drum section not included in evaluation

** Approximate

ACP SYSTEM DESCRIPTION

Introduction

Figure 23 is a schematic diagram of the ACP flight control hydraulic system. Component layout is defined in Figure 24. Two completely separate independent and redundant full-time systems are utilized. Each of the two systems shall by itself, be capable of providing the required flight control and stability augmentation functions. Appendix B provides the rationale for selecting the ACP system.

One hydraulic power generator and control system is located at each end of the helicopter, with one pump on each rotor transmission and a control module nearby. The rotor control actuators are dual units, similar to those of the CH-47C but with seal and bearing improvements. Hydraulic tubes are routed through the drive shaft tunnel area, above the cabin, to connect each power generator and control system to the rotor control actuators that are situated at the opposite end of the helicopter. Fluid transmission lines are located so that there is at least a 14-in. separation between the lines of the two flight control hydraulic systems.

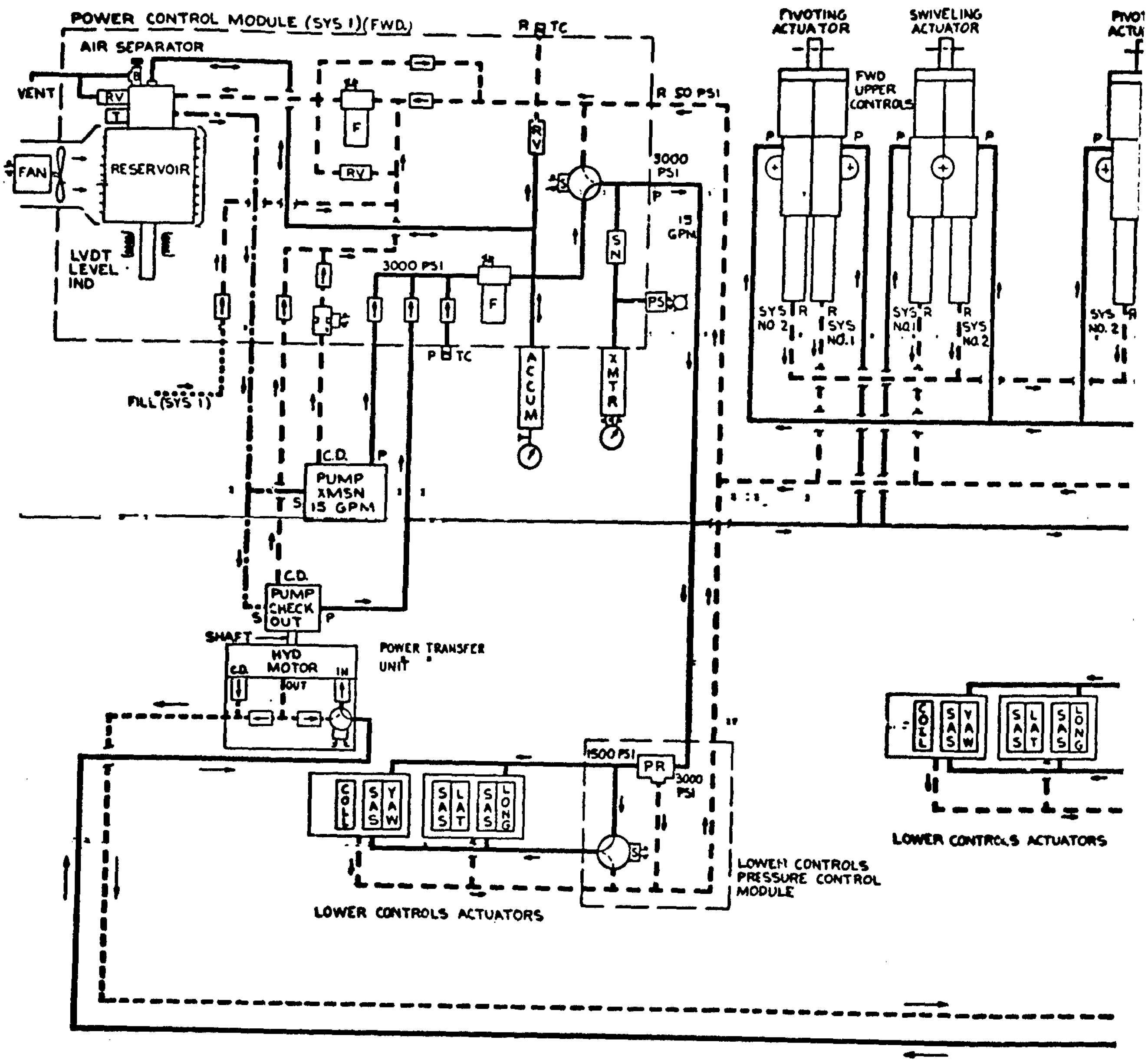
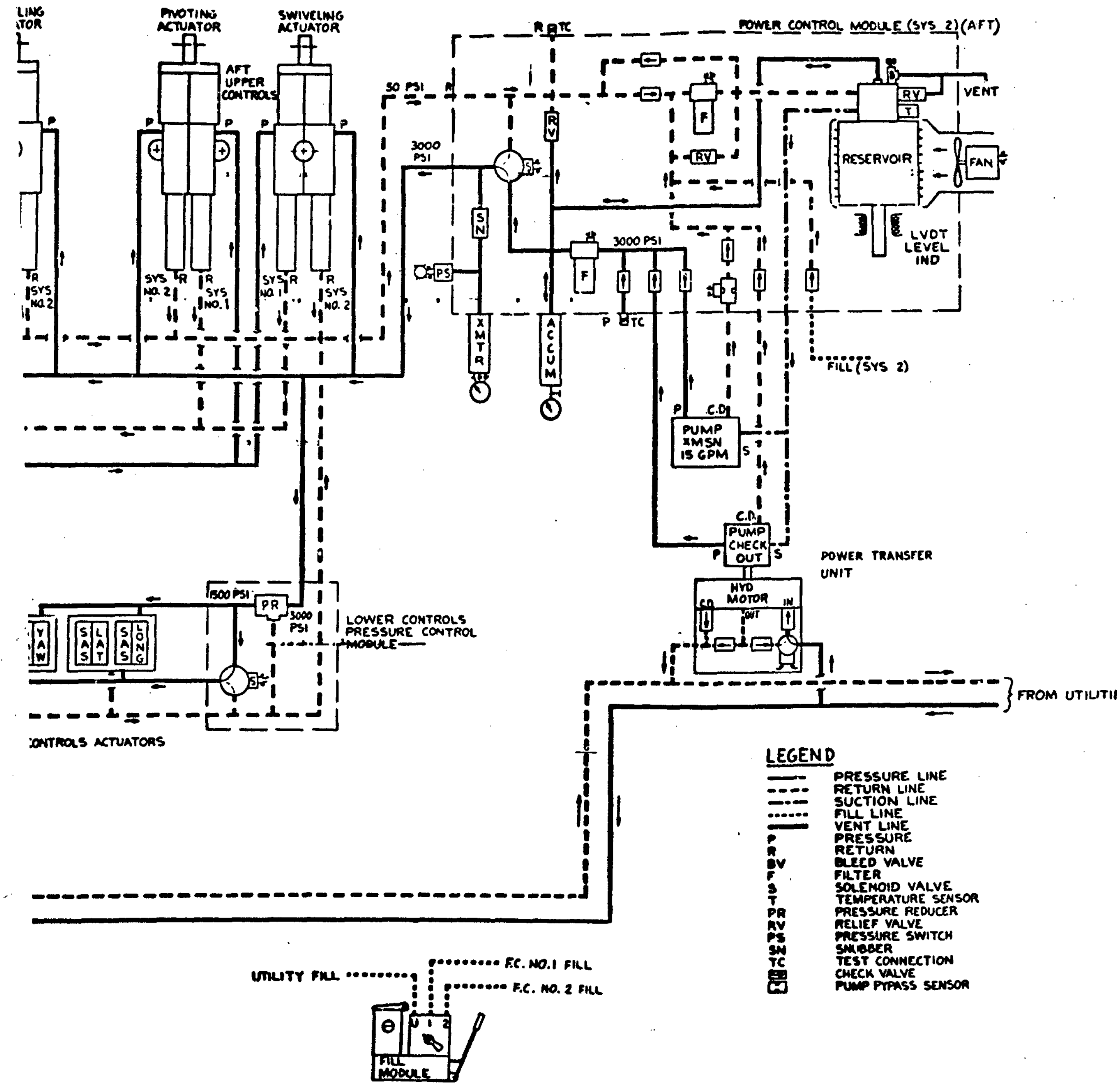


Figure 23. Advanced Conventional Pressure Flight-Control Hydraulic System Schematic.


PIVOTING ACTUATOR
SWIVELING ACTUATOR
AFT UPPER CONTROLS
POWER CONTROL MODULE (SYS 2)(AFT)
50 PSI
3000 PSI
RESERVOIR
FAN
VENT
LVDT LEVEL IND
SN
PS
XMTR
ACCUM
3000 PSI
FILL (SYS 2)
PUMP XMSN 15 GPM
PUMP CHECK OUT
POWER TRANSFER UNIT
HYD MOTOR
1500 PSI
PR
3000 PSI
LOWER CONTROLS PRESSURE CONTROL MODULE
YAW
SAS LAT
SAS LONG
CONTROLS ACTUATORS
FROM UTILITI
UTILITY FILL
F.C. NO.1 FILL
F.C. NO. 2 FILL
FILL MODULE
LEGEND
PRESSURE LINE
RETURN LINE
SUCTION LINE
FILL LINE
VENT LINE
P PRESSURE
R RETURN
BV BLEED VALVE
F FILTER
S SOLENOID VALVE
T TEMPERATURE SENSOR
PR PRESSURE REDUCER
RV RELIEF VALVE
PS PRESSURE SWITCH
SN SNUBBER
TC TEST CONNECTION
CHECK VALVE
PUMP PYPASS SENSOR

(1)

(2)

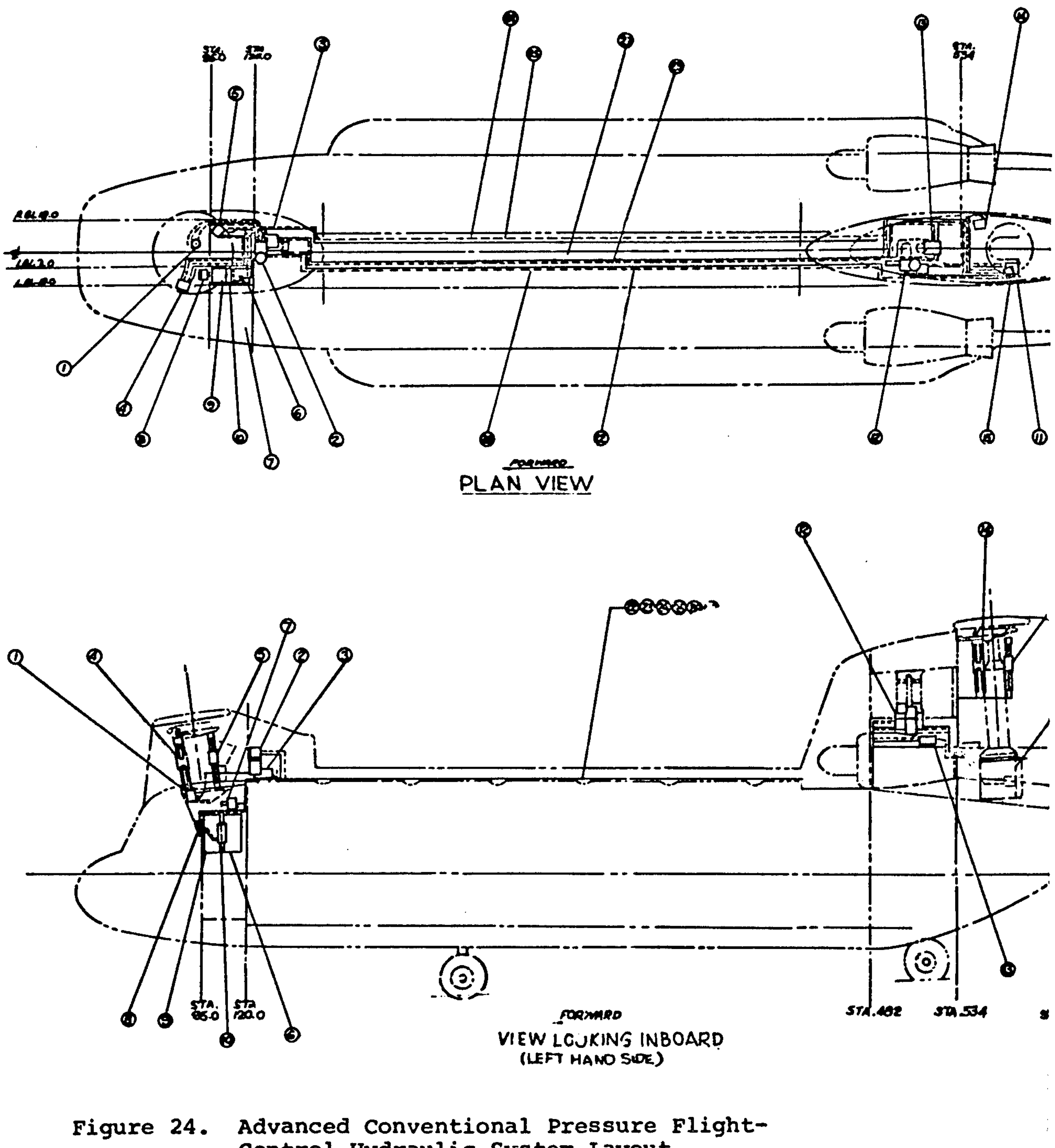
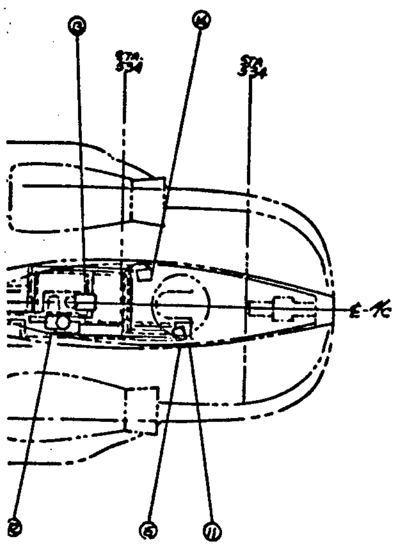
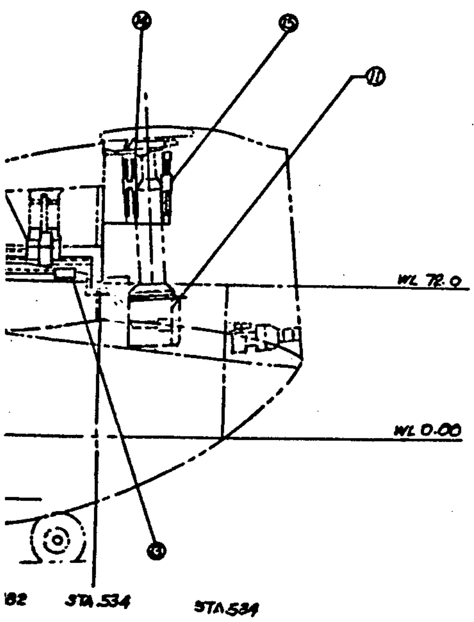


Figure 24. Advanced Conventional Pressure Flight-Control Hydraulic System Layout.





CODE – COMPONENTS AND LINES

1	FLIGHT CONTROL PUMP – SYSTEM 1 – FORWARD
2	FLIGHT CONTROL – SYSTEM 1 – POWER CONTROL MODULE – FORWARD
3	FLIGHT CONTROL – SYSTEM 1 – POWER TRANSFER UNIT – FORWARD
4	UPPER BOOST – SWIVELING – ACTUATOR – FORWARD
5	UPPER BOOST – PIVOTING – ACTUATOR – FORWARD
6	LOWER CONTROL – ACTUATORS (ROLL AND PITCH)
7	LOWER CONTROL – MODULE – SYSTEM 1
8	LOWER CONTROL – MODULE – SYSTEM 2
9	LOWER CONTROL – ACTUATORS (YAW AND THRUST)
10	LOWER CONTROL – MANIFOLD – SYSTEMS 1 AND 2
11	FLIGHT CONTROL PUMP – SYSTEMS 1 AND 2
12	FLIGHT CONTROL – SYSTEM 2 – POWER CONTROL MODULE – AFT
13	FLIGHT CONTROL – SYSTEM 2 – POWER TRANSFER UNIT – AFT
14	UPPER BOOST – SWIVELING – ACTUATOR – AFT
15	UPPER BOOST – PIVOTING ACTUATOR – AFT
22	FLIGHT CONTROL – SYSTEM 1 – RETURN LINE
23	FLIGHT CONTROL – SYSTEM 1 – PRESSURE LINE
24	FLIGHT CONTROL – SYSTEM 2 – RETURN LINE
25	FLIGHT CONTROL – SYSTEM 2 – PRESSURE LINE
26	UTILITY SYSTEM – RETURN LINE
27	UTILITY SYSTEM – PRESSURE LINE

(1)

(2)

System Definition

The ACP flight control hydraulic system shall consist of two completely separate subsystems; each capable of providing all necessary flight control functions. Each subsystem includes the following major components.

1. Transmission driven pump for flight operation.
2. Utility hydraulic driven power transfer unit (PTU) for system ground operations and limited-capability in-flight backup.
3. Power control module which includes a reservoir and cooler fan assembly.
4. Lower pressure control module, controlling pressure and flow to the integrated lower controls actuators.
5. Integrated power control actuators, providing cockpit controls boost in pitch, roll, yaw, and thrust, plus SAS actuation in pitch, roll, and yaw.
6. Upper control actuators providing control of the swashplates.
7. Hydraulic maintenance panel, providing an integrated display of vital flight control hydraulic system parameters.

System Features

The flight-control hydraulic system will have these general features:

1. Flight-Control Hydraulic Redundancy

   In order to maximize the separation of the two flight control hydraulic systems, the pumps shall be driven by separate spline shafts, one in the forward transmission and one in the aft transmission. The objective shall be to prevent the failure of a single spline shaft from causing loss of both systems.

2. Modularization

   The standard hydraulic components, traditionally distributed throughout the systems, shall be packaged into a single housing. Certain units will be packaged as cartridges which can be easily inserted and removed from the module. A cartridge is a hydraulic

component having a standardized outline. The components packaged in the modules shall comprise reservoirs, accumulators, coolers, filters, bleed valves, solenoid valves, pressure reducers, regulators, test connections and fluid distribution manifolds. The objective of modularization shall be to minimize the number of hoses, tubes, mounting brackets and connection fittings in order to improve maintainability, vulnerability, reliability, safety and maintenance costs.

3. Integration of Actuators

The dual lower boost actuators and dual SAS actuators shall be integrated into a single actuator package. The objective shall be to reduce the number of actuators and minimize the number of hoses and fittings in order to maximize maintainability, reliability, and safety, and to reduce maintenance costs. This actuator will be an exact copy of the one planned for the YCH-47D Program.

4. Swaging of Lines

In most applications, swaged fittings shall be used on hydraulic lines instead of threaded fittings. The objective shall be to improve maintainability and reliability by minimizing the probability of fluid leakage. All pressure and return lines shall use stainless-steel tubing, and fittings.

5. Integrated Troubleshooting Indication

A hydraulic maintenance panel shall be provided to display the vital parameters of the flight control hydraulic system. The panel shall provide continuous indication of pressure, reservoir fluid level, cooler inlet fluid temperature, need for filter replacement and need for pump replacement.

6. Single Point Ground Servicing

Servicing of the utility hydraulic system and both flight control hydraulic systems shall be made possible from a single fill module without intermixing of fluids in the three separate systems. The ground servicing lines shall be depressurized when not in use.

Component Descriptions

ACP flight control hydraulic system components shall be configured as follows:

1. Hydraulic Power Control Module

   The unit shall receive fluid from the flight control pump and distribute it at the pressures and flows specified below. The module shall have a single housing, except that the cooler fan and reservoir shall bolt onto the main module housing. Hydraulic fluid filtration shall be 5 microns absolute in accordance with MIL-F-8815C using disposable elements. The cartridge components within the module shall be designed to meet the specifications of MIL-H-8775C. It shall be possible to easily remove the complete module from the helicopter, or the cartridges from the module housing, while mounted in the helicopter. All sensors (pressure, temperature, fluid level) plus the accumulator and filter shall be removable from the module during on-aircraft corrective maintenance tasks. The module shall contain a reservoir level indicator, temperature probe, air separator, 5 micron pressure and return filters, return filter bypass valve, filter contamination indicators, pump replacement indicator, pressure switch, pressure relief valve, accumulator, solenoid shutoff valve, pressure snubber and transmitter, reservoir relief valve, bleed valve, and an integrated reservoir/cooler unit with a removable electric motor and fan assembly. Troubleshooting aids, as shown in Figure 23, shall be provided to reduce fault isolation task times. The module shall provide sufficient fluid cooling to prevent the fluid temperature at the hottest spot in the system from rising above 275°F in a 125°F ambient environment.

2. Flight-Control Upper Boost Actuators

   The flight control upper boost actuators (swiveling and pivoting) shall be designed in accordance with MIL-H-5440F, Type II (modified to a -50°F limit) MIL-C-5503C, MIL-H-8775C and the performance criteria of the CH-47C. The upper boost actuator shall be a dual hydraulic power actuator with individual manifolds and cylinders for each hydraulic system to provide system isolation and crack propagation protection. The actuator shall be controlled by a three-way jam-proof servo valve. The jam-proof servo valve shall

incorporate linear flow gain characteristics and shall preclude loss of actuator control due to valve jams.

a. Stroke - The actuator stroke shall be 12.5 inches.

b. Force - Each section of the actuator shall have a stall capacity of 3000 lb in compression and 2,250 lb in extension along its entire stroke, for pressure differentials across the piston of 3000 psi.

3. Lower Controls Pressure Control Module

The module shall have a single housing with mounting provisions to enable installation in the CH-47C SAS compartment of the No. 1 and No. 2 flight control systems. The module shall contain pressure reducer and SAS shutoff valve cartridges. The unit shall be capable of reducing the main flight control system pressure from 3000 to 1500 psi (+50/-100 psi) and of shutting off the pressure supply to the SAS actuators. The cartridges shall be designed in accordance with the specifications of MIL-H-8775C.

4. Flight-Control Integrated SAS and Lower Boost Actuator

The integrated lower control actuator (ILCA) shall be designed in accordance with MIL-H-5440F, Type II, (Modified to -50°F/+275°F), MIL-C-5503C, MIL-H-8775C, and the performance criteria of the CH-47C. The IlCA unit shall consist of a dual hydromechanical power actuator with jam-proof servo valves and a dual differential electrohydraulic SAS actuator. Each hydraulic system shall be isolated by separate manifolds and cylinders to provide crack propagation protection. The unit shall convert mechanical and/or electrical input signals to output motion proportional to the input.

a. Stroke - The output stroke of the lower boost section of the actuator shall be +2.25 inches. The output stroke of each half of the dual electrohydraulic actuator section shall be ±.50 inch.

b. Force - Each section of the lower boost actuator shall be able to provide forces of up to 175 lb

along its entire stroke, for pressure differentials across the piston of 1500 psi. Each section of the SAS actuator shall be able to provide forces of up to 570 lb along its entire stroke, for pressure differentials across the piston of 1500 psi.

5. Flight Control Pumps

The No. 1 and No. 2 flight control pumps shall be previously proven units, modified as required from service data to improve their reliability and maintainability. The two pumps shall be of the variable-delivery type, compensated for 3050 psi, and meeting the following operating characteristics:

Flow at 5200 RPM	-	15.5 gpm minimum
Pressure	-	3050 $\pm$50 psi at zero flow
	-	2900 psi minimum at full flow
Minimum MTBF	-	2500 hours
Step Response	-	Peak to minimum flow, .05 second maximum

6. Flight Control Power Transfer Unit

The flight-control checkout unit shall be a fixed-displacement pump, driven by a fixed-displacement motor which shall derive its power from the utility hydraulic system. The fixed-displacement pump is connected to the flight-control system and is used to power the actuators prior to starting the main engines and rotor. The pump can provide backup flight control capability in the event a primary flight control hydraulic pump is disabled, but due to a low fluid delivery rate, only limited control movements will be possible. A mechanical shaft separates the flight-control checkout pump from the motor and its controls. No hydraulic interconnection shall exist between the motor and the pump. The motor shall contain an integrated solenoid shutoff valve, check valves, and a flow limiter. The maximum required flow from the utility hydraulic system will be 10.7 gpm and 3300 psi (nominal). The PTU will

supply 3.75 gpm at 3000 psi (nominal) to the flight control hydraulic system.

7. Hydraulic Maintenance Panel

The hydraulic maintenance panel shall provide an integrated centralized display of the following parameters for each of the two flight control hydraulic systems.

a. Hydraulic System Pressure - Gage pressure indication of the supply pressure at the power control module in psi.

b. Reservoir Fluid Level - Gage level of fluid in the reservoir in inches.

c. Fluid Temperature - Temperature of pump case drain at the power control module in degree Fahrenheit.

d. Filter Replacement Need - Warning light indication of activation of the pressure filter and the return filter overpressure drop (need for replacement) mechanism.

e. Pump Replacement Need - Warning light indication of activation of the pump case drain excessive flow (need for replacement) sensor.

8. Fill Module

The fill module shall provide the capability of filling the two flight control hydraulic systems and the utility hydraulic system. It shall comprise a filler assembly, a single-stage hand pump,and a valve for selection of any of the three hydraulic systems for filling.

General System Characteristics

1. Pressure

Each hydraulic system shall provide the required input pressure to its primary controls and stability augmentation actuators throughout the specified flow range, as follows:

Upper boost actuators - 2 swivel and 2 pivot - 3050 (+50/-250) psi

Stick boost actuators - pitch,roll,yaw and thrust - 1500 (+50/-100) psi

Stability augmentation actuators - pitch,roll,yaw - 1500 (+50/-100) psi

2. Flow Range

The flow capability range shall be as follows:

Upper boost actuators (4 units)	0 to 3.6 gpm per unit
Lower boost actuators (4 units)	0 to 0.3 gpm per unit
Stability augmentation actuators	0 to 1.0 gpm total

The flow capability of the flight control hydraulic system shall be 15 gpm. This flow capability is less than the combined maximum flows to the actuators because the condition of all actuators requiring maximum flow simultaneously never occurs. 15 gpm is the CH-47C flight control hydraulic capability.

3. Altitude

The flight control hydraulic systems shall be pressurized to eliminate altitude restrictions on their operation. Pressurization shall be via a spring-loaded reservoir piston. The design shall include a device to allow securing the spring during certain component replacement tasks in order to reduce the need for draining and servicing the reservoir during maintenance. The device shall be so configured that it cannot inadvertently be left engaged during system operation.

4. Temperature

The maximum hydraulic fluid temperature throughout the system shall not be allowed to exceed 275°F, in a 125°F ambient environment.

ACP Hoist System

Figure 25 is a schematic of the ACP hoist system. This system has several advantages over the CH-47C hoist system that was described earlier.

1. All hydraulic components, except the motor and winch, are contained in one module.

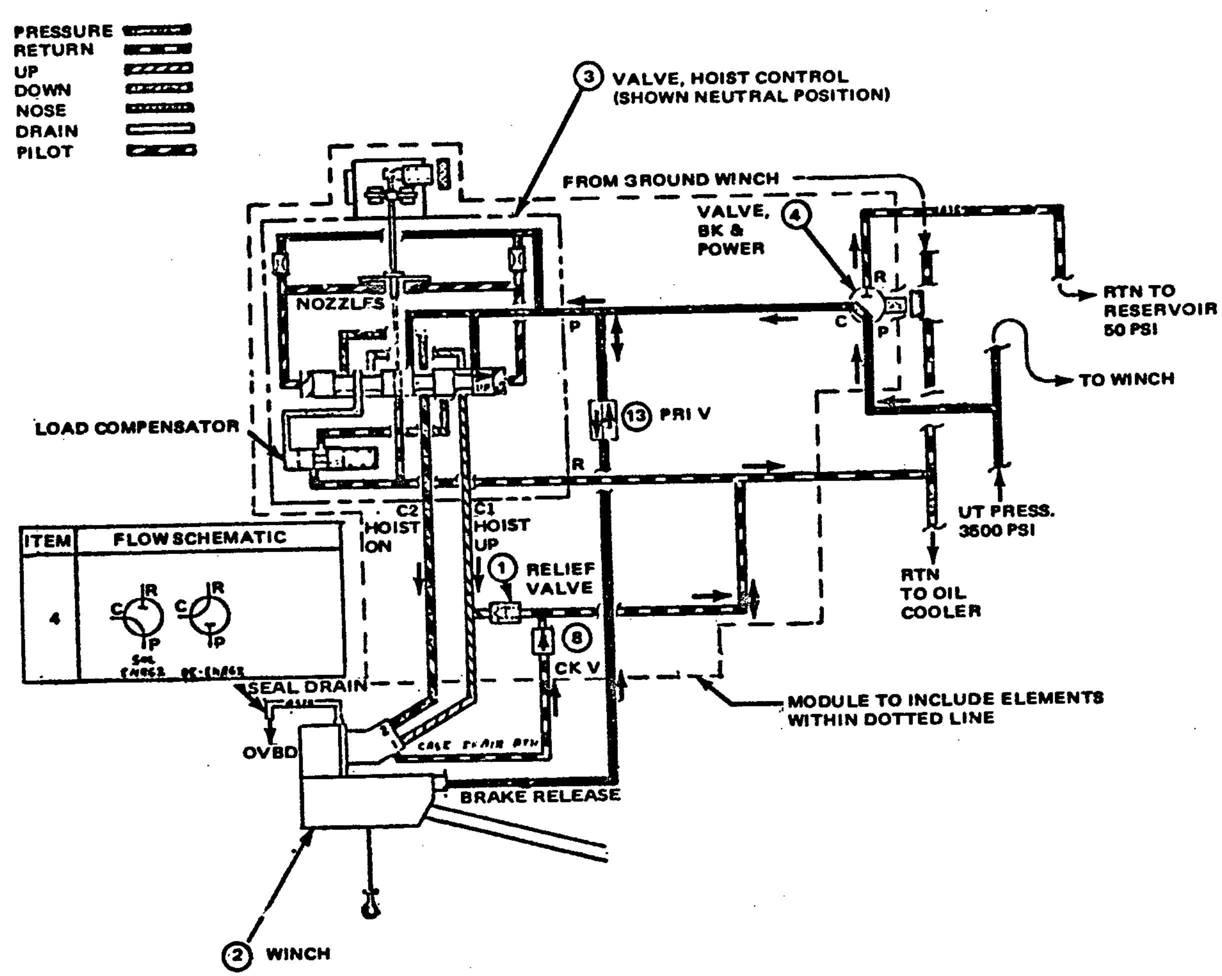


Figure 25. Schematic - Winch System.

2. The new control unit is a servo valve that has a load compensator. It offers linear control between 15- and 300-ft/min reel speeds.

3. The system automatically reduces hoist speed at a distance of 20±5 feet prior to the reel-in limit. This is accomplished by a limit switch that signals the servo valve when the slow-down point is reached.

4. In the event that electrical control of the hoist is lost, the servo valve can be operated manually.

5. A priority valve has been added that precludes release of the brake at low hydraulic pressures. This will eliminate the possibility of the drum starting to unwind before the motor receives sufficient power to support the load.

The hoist system receives hydraulic power from the utility hydraulic system. All hydraulic components, except for the motor and winch assembly, are located in one module that is positioned on the left-hand wall of the CH-47 heater compartment. The module concept is similar to that of the flight control hydraulic system lower control module. The basic one-piece unit is bolted to the aircraft structure, and the various valves are plug-in cartridges. The module contains:

1. Brake and power solenoid valve, 3-way, normally open
2. Winch control valve, an electrohydraulic servo valve with load compensating valve and manual override provisions
3. Priority valve
4. Relief valve
5. Check valve

The motor and winch assembly are located over the forward cabin door, positioned by a support structure that extends outward over the door. The support structure is similar to that used on the Canadian CH-147, except that provision is made for collapsing the structure in order to perform maintenance on the motor and winch. The general system characteristics are as follows:

1. Load capacity -- 600 lb
2. Cable speed -- 300 fpm
3. Usable cable -- 245 ft
4. Flow rate -- 6.0 gpm
5. Brake release press. -- 150 psi(full release 1200 psi)
6. Hyd press ΔP at module parts -- 3100 psi/min
7. Priority valve opens -- 2000 psi
8. Relief valve - full flow -- 4480 psi/max
   Relief valve - reseat -- 4200 psi/min
9. Control valve ΔP at full flow -- 400 psi/max
10. Control valve voltage re[illegible]ired -- 28-30 V/DC
11. Control valve current reauired -- 20-0-20 ma
12. Solenoid valve ΔP at ful. flow -- 10 psi/max
13. Solenoid valve voltage require[illegible] -- 28-30 V/DC
14. Solenoid valve current -- [illegible].75 amp at [illegible] V/DC, 70°F
15. Check valve cracks -- 2 to 10 psig

VHP SYSTEM DESCRIPTION

System Description

The 8000-psi improved flight contrcl system is comprised of dual independent systems, each providing required flight control and stability augmentation capabilities. A schematic diagram is shown in Figure 26; the system installation is given in Figure 27. Detailed calculations and assumptions made in establishing the system configuration may be found in Reference 43.

The two independent systems are functionally similar to the baseline systems. No. 1 system is powered by a rotor transmission-mounted hydraulic pump located in the aft end of the aircraft. This pump receives fluid from and supplies high-pressure fluid to a reservoir module which contains virtually all the system components. Filtered high-pressure fluid is routed locally to the aft upper rotor-control actuators which are 8000-psi versions of the CH-47C actuators.

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[43] APPLICATIONS STUDY OF LIGHTWEIGHT HYDRAULIC SYSTEMS TO HELICOPTERS, NR 76H-81, Columbus Aircraft Division of Rockwell International Corporation, October 1976.

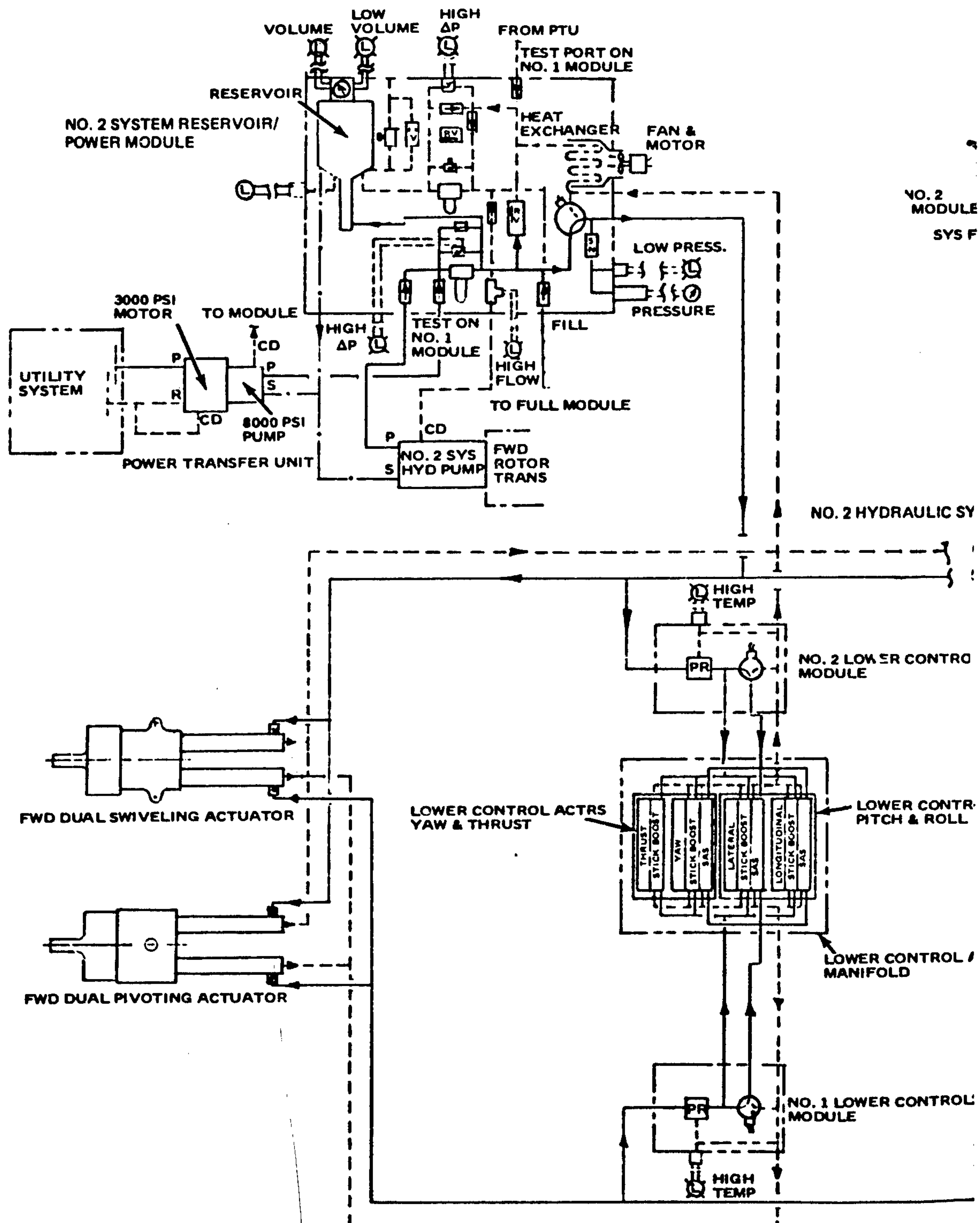
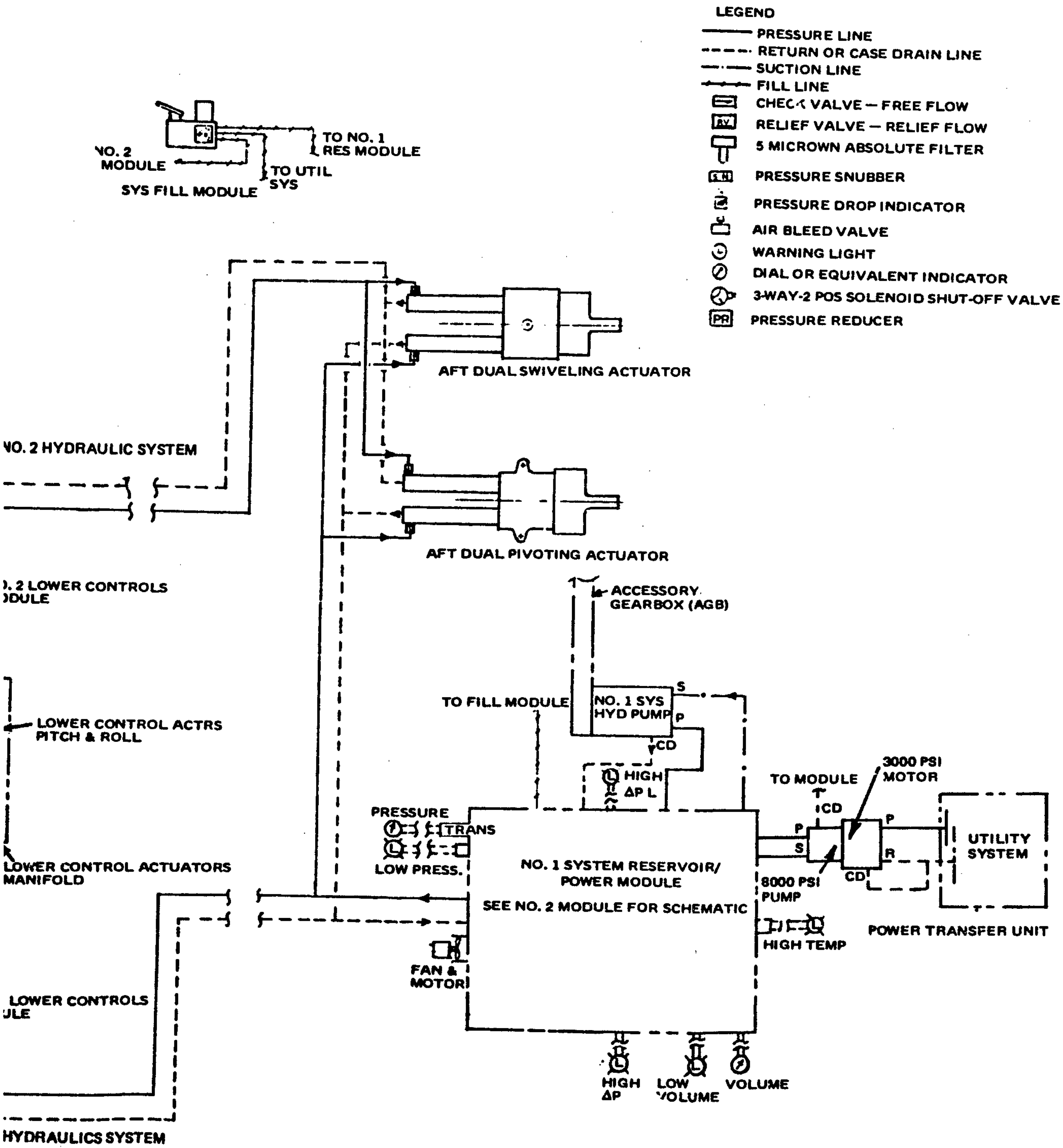


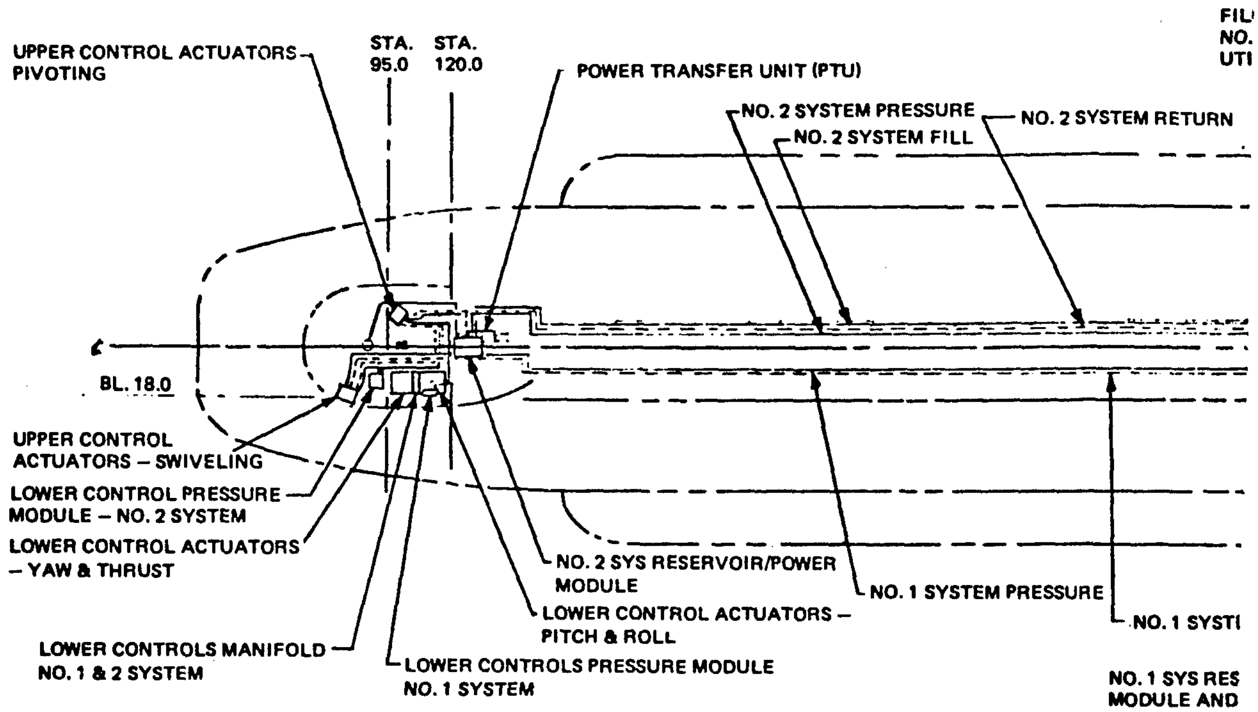
Figure 26. Very High Pressure Flight-Control Hydraulic System Schematic.



LEGEND
PRESSURE LINE
RETURN OR CASE DRAIN LINE
SUCTION LINE
FILL LINE
CHECK VALVE — FREE FLOW
RELIEF VALVE — RELIEF FLOW
5 MICROWN ABSOLUTE FILTER
PRESSURE SNUBBER
PRESSURE DROP INDICATOR
AIR BLEED VALVE
WARNING LIGHT
DIAL OR EQUIVALENT INDICATOR
3-WAY-2 POS SOLENOID SHUT-OFF VALVE
PRESSURE REDUCER
TO NO. 1 RES MODULE
NO. 2 MODULE
TO UTIL SYS
SYS FILL MODULE
AFT DUAL SWIVELING ACTUATOR
NO. 2 HYDRAULIC SYSTEM
AFT DUAL PIVOTING ACTUATOR
. 2 LOWER CONTROLS ODULE
ACCESSORY GEARBOX (AGB)
LOWER CONTROL ACTRS PITCH & ROLL
TO FILL MODULE
NO. 1 SYS HYD PUMP
S
P
CD
HIGH ΔP L
TO MODULE
CD
3000 PSI MOTOR
PRESSURE
TRANS
LOW PRESS.
LOWER CONTROL ACTUATORS MANIFOLD
NO. 1 SYSTEM RESERVOIR/ POWER MODULE
SEE NO. 2 MODULE FOR SCHEMATIC
P
S
P
R
CD
UTILITY SYSTEM
3000 PSI PUMP
HIGH TEMP
POWER TRANSFER UNIT
FAN & MOTOR
LOWER CONTROLS ULE
HIGH ΔP
LOW VOLUME
VOLUME
HYDRAULICS SYSTEM

(4)

(3)



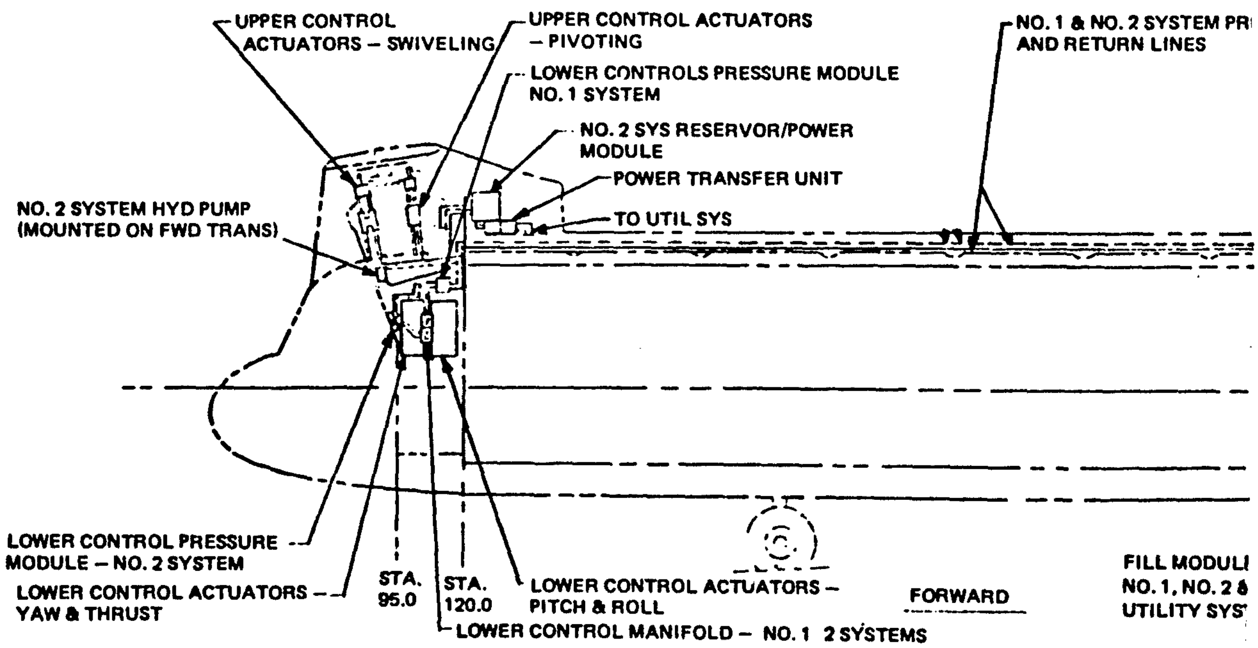
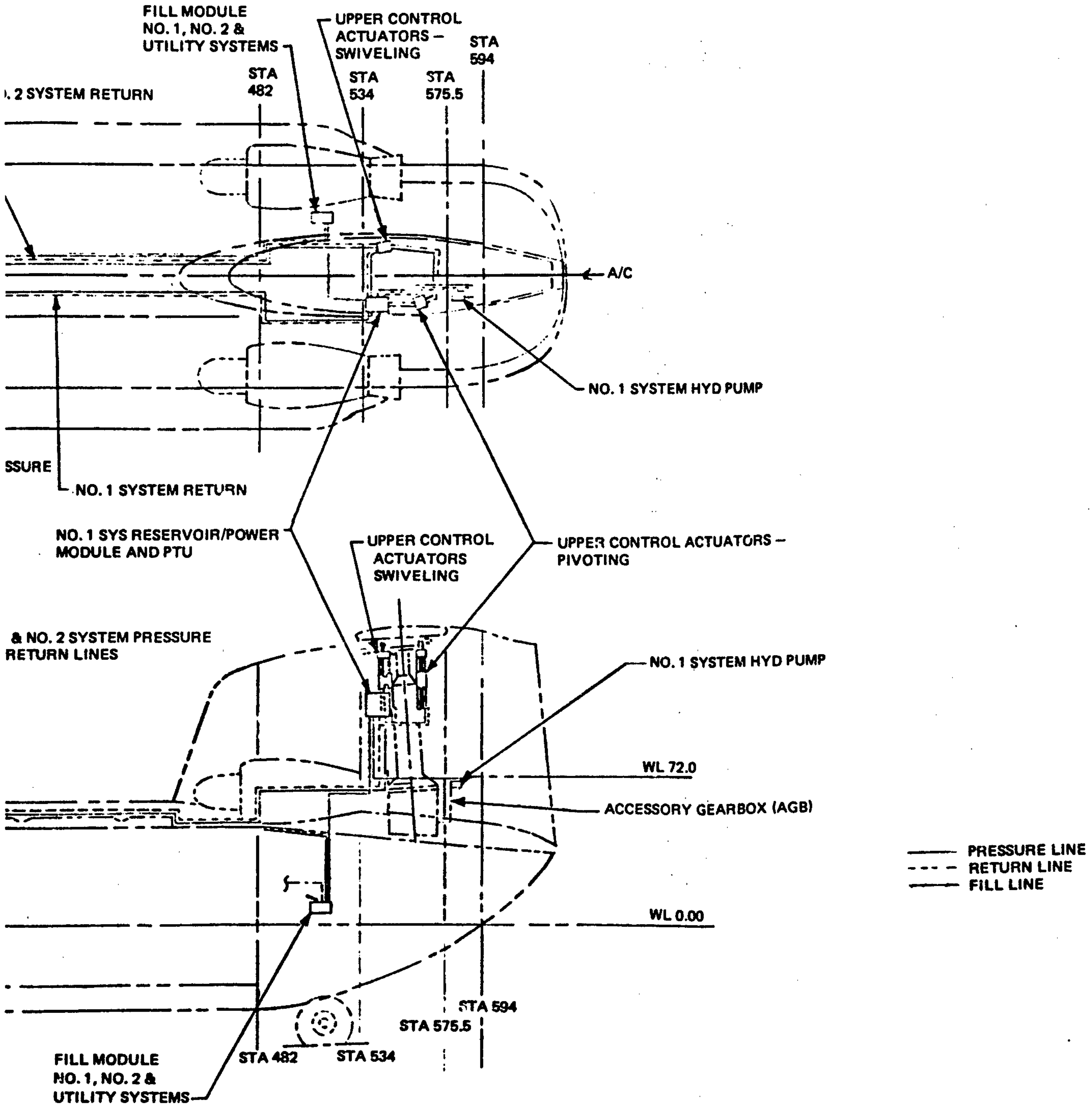


Figure 27. Very High Pressure Flight-Control Hydraulic System Layout.

(1)



FILL MODULE
NO. 1, NO. 2 &
UTILITY SYSTEMS
UPPER CONTROL
ACTUATORS –
SWIVELING
STA 594
STA 482
STA 534
STA 575.5
. 2 SYSTEM RETURN
A/C
NO. 1 SYSTEM HYD PUMP
SSURE
NO. 1 SYSTEM RETURN
NO. 1 SYS RESERVOIR/POWER
MODULE AND PTU
UPPER CONTROL
ACTUATORS
SWIVELING
UPPER CONTROL ACTUATORS –
PIVOTING
& NO. 2 SYSTEM PRESSURE
RETURN LINES
NO. 1 SYSTEM HYD PUMP
WL 72.0
ACCESSORY GEARBOX (AGB)
PRESSURE LINE
RETURN LINE
FILL LINE
WL 0.00
STA 594
STA 575.5
STA 482
STA 534
FILL MODULE
NO. 1, NO. 2 &
UTILITY SYSTEMS

(1)

Fluid is also routed from the reservoir module forward to the forward rotor upper control actuators and also to the lower control actuator module. This module contains controls for the 1500-psi lower control actuators (SAS and stick boost). A hydraulic power transfer unit supplies power from the utility system--without intermixing fluids--for ground checkout of the system, plus limited flight control backup. The No. 2 system is similar to No. 1, except that the hydraulic reservoir module is located in the forward pylon near the pump.

Although functionally similar to the CH-47C baseline system, the 8000 psi improved system contains features and system modifications directed toward increasing system reliability and survivability, while reducing overall system maintenance requirements. The modifications and major features are:

1. Upper Boost Actuators - Rip-stop design of the actuator valve and cylinder body are provided. This feature is added to prevent propagation of a single crack which could ultimately cause a dual failure.

2. Integrated Lower Control Actuators - The present dual stick-boost and SAS actuators are combined into one actuator. This feature reduces the number of actuators by one-half and significantly reduces flexible hose requirements.

3. Modularization - All system components, normally located throughout the system, are combined in modules. The modules contain virtually all system components with the exception of the pumps and actuators. Components are of the removable cartridge type, where removal can be accomplished without disconnecting lines. This feature eliminates a large number of lines, fittings and hoses.

4. Tube Connections - Permanent joints are used in all line runs between modules, except where line removal may be required for routine maintenance. In these areas and at the modules where separable fittings are required, lipseal type connectors are used. These fittings resist loosening under vibration and simplify installation/removal of lines. Murphy proof plumbing arrangements are provided through the use of "jump size" tube fittings.

5. Remote Indicators - Remote indications of critical system parameters are provided for maintenance purposes. System pressure, fluid temperature, pump case drain flow, filter bypass status, and reservoir level will be displayed on a maintenance panel. This is in

addition to normal system status indications provided in the cockpit.

6. Fill Module - A fill module, accessible from within the aircraft, will permit servicing reservoirs from a single location. A selector valve, filter and hand pump will provide the capability of replenishing any one of the three hydraulic system reservoirs with new fluid.

7. System Separation - To increase aircraft reliability and survivability, the system pumps are mounted on separate pads--one on the forward rotor transmission and one on the aft rotor transmission. The reservoir modules, which contain all the power generation controls, filters, etc., are located at opposite ends of the aircraft, one in each pylon, thereby providing maximum physical and functional separation of the power generation systems. The fore and aft line runs for each system are routed adjacent to the fore and aft drive shafting and separated by approximately 14 inches.

Additionally, each system contains the following features or capabilities:

1. Operating Pressure - 8000 psi throughout except for the lower controls actuators which operate at 1500 psi.

2. Operating Temperature - The system is designed to operate with fluid temperatures ranging from -50°F to +275°F and ambient temperatures from -50 to +125°F.

3. Hydraulic Fluid - MIL-H-83282

4. System Flow Capacity - Each system pump is sized to provide sufficient flow for simultaneous operation of system actuators. Pump capacity is 7.0 gpm at 8000 rpm.

5. System Shutoff Valve - The system contains a fail-safe shutoff valve which can be used to depressurize the entire system downstream of the power circuit in the event of a leak or for single system operation simulation.

6. SAS Shutoff Valve - Shutoff valves are provided to depressurize the SAS actuators in the event of a malfunction or to simulate loss of the SAS system.

7. Ground Checkout Capabilities - Each system may be operated for ground checkout without the need for ground support equipment by means of the APU and a PTU.

8. Altitude - The system is designed so that the hydraulic system will not impose altitude restrictions on aircraft operation.

Component Descriptions

Descriptions of components in the 8000-psi improved flight control system are given in the following paragraphs. The descriptions are for components in one system, but are applicable to both systems except where stated otherwise.

Reservoir Module

The reservoir module contains all the power generation system components, both high- and low-pressure, with the exception of the system pump, Figure 26. All components are designed to the general requirements of MIL-H-8775, except as modified for 8000 psi. All components are cartridge types, completely inserted into the module housing or screwed or bolted on externally. The majority of components will be replaceable without requiring the removal of the module from the aircraft during maintenance or troubleshooting.

As shown in Figure 26, the module contains a heat exchanger and fan sized to provide sufficient cooling (approximately 310 BTU/min) to maintain maximum system temperature below +275°F with a +125°F ambient temperature. The heat exchanger and fan will be removable from the module.

The reservoir module contains the following functional components:

- Bootstrap type reservoir, 35 psig
- Heat exchanger and fan
- System relief valve
- Low pressure relief valve (overboard)
- Return filter bypass relief valve
- 5-micron absolute pressure and return filters
- System shutoff valve

- Reservoir air bleed valve
- Misc check valves (7)
- Pressure snubber

In addition, the module contains the following components to provide for remote indication of reservoir/module operating status:

- Reservoir level sensor (LVDT or equivalent)
- Reservoir low level switch
- System pressure switch (8000 psi)
- System pressure transmitter/transducer (8000 psi)
- Filter ΔP switch (2)
- Module fluid temperature switch
- Pump case flow (ΔP) switch

The module contains 11 external ports, two of which are for test purposes. The remaining ports are connected to system plumbing by Rosan/Dynatube lipseal type fittings. The fitting style and port locations will permit rapid component installation/removal. The module can be removed by disconnecting nine lines at the module, separating the electrical connectors, and unfastening three mounting bolts.

Hydraulic Pump

The hydraulic pump is a conventional design in general accordance with MIL-F-19692. It is a constant-pressure (8000-psi) variable displacement axial piston type design with flat cut-off pressure regulation. Pump requirements are summarized below:

• Rated pressure	8000 ± 1000 psi
• Pressure at rated delivery	7850 psi (min)
• Rated delivery	7.0 gpm
• Rated speed	8000 rpm
• Response (step)	0.050 sec
• Overall efficiency	85% (min)

•	Inlet pressure	35 psig (min)
•	Case drain leakage	1.0 gpm (max)
•	Mounting flange	AND10261 type X1-B
•	Rated temperature	+275°F
•	Weight (maximum dry)	6.8 lb

Upper Control Actuators

The 8000-psi upper control actuators (dual swiveling and dual-pivoting) will be designed in general accordance with MIL-H-5440 and MIL-C-5503. Steel cylinder barrels and valve housings will be used. The actuators and valves will be a rip stop design to preclude inter-system crack propagation. Actuator control is provided by a three-way hydro-mechanical servo valve with linear flow gain characteristics. The valve/actuators will be physically and functionally interchangeable with the existing CH-47C actuators.

Actuator general requirements are summarized below:

•	Operating pressure	8000 psi
•	Proof pressure	12000 psi
•	Valve travel	±.125 in
•	Valve friction	2.5 lb (max)
•	Valve level limit load	225 lb
•	Valve dead band	±.003 in
•	Actuator stroke	12.5 in
•	Actuator output (min/system) (swiveling)	
	Extend	3422 lb
	Retract	2424 lb
•	Actuator no-load open loop gain	60 rad/sec
•	Actuator loading	See Table 13.

Integrated Lower Control Actuators

The 1500-psi lower control actuators are identical to the units defined in the ACP system.

Power Transfer Unit

The power transfer units will transmit hydraulic power from the 3000-psi utility system to the 8000 psi flight control systems without intermixing of system fluids. Each unit will consist of a fixed displacement 8000 psi hydraulic pump mechanically coupled to a fixed displacement 3000-psi hydraulic motor. Motor controls will consist of a shut-off valve, a flow-limiting device, and check valves. The PTU shall have the following operating characteristics:

• Max rated speed		8000 rpm
• Flow at rated speed		
	Output	2.30 gpm (min)
	Input	8.60 gpm (max)
• Pressure at rated speed		
	Output	8000 ±100 psi
	Input	3000 ±100 psi
• Flow limiter setting		9.0 gpm (max)

Flow will vary automatically as required by the 8000-psi system. The unit shall be designed to operate smoothly at flows down to 0.2 gpm.

Lower Control Module

The module contains a cartridge-type, three-way, two-position, 1500-psi solenoid shutoff valve and an 8000- to 1500-psi pressure reducer with a 3.0-gpm capacity. A temperature sensor is provided to monitor pressure reducer return fluid temperature to detect reducer malfunction. All components shall be designed in general accordance with MIL-H-8775, except as modified for 8000 psi.

Fill Module

The fill module will accept a standard one-quart can of hydraulic fluid and have provisions for piercing and sealing the can. The unit contains a hand pump, 5-micron

absolute filter, and three-way directional valve for selecting one of the three systems to be serviced.

Hydraulic System Maintenance Panel

The hydraulic systems shall have a central location for display of all maintenance oriented parameters from the outputs of the following diagnostic sensors in each of the two systems:

- Reservoir Level - An appropriate dial or equivalent readout will indicate reservoir fluid level. Full and refill levels will be clearly marked.

- Filter Element ΔP - A warning light for each of the two filter ΔP switches, located in the reservoir module, will indicate excessive element pressure drop and flag filter element replacement.

- Temperature - Warning lights will indicate actuation of the reservoir module fluid temperature switch and lower controls temperature switch.

- Pressure Gage - A pressure gage will provide indication of system pressure at the reservoir module. This is a repeater gage and duplicates the pressure indicator provided in the cockpit.

- Pump Case Flow - A warning light energized by a ΔP switch will indicate excessive flow in the pump case drain line.

VHP Hoist System

The 8000 psi system is identical to the increased capacity CH-47C baseline hoist system. No modularization or improvements were employed; instead, direct substitutions were made--line for line, component for component. System design data are summarized below:

• Load capacity	600 lb
• Cable speed	300 ft/min
• System pressure	8000 psi
• Rated flow	2.25 gpm
• ΔP across motor at 2.25 gpm	5876 psi
• Motor displacement	0.041 CIPR

o	Motor speed	12,000 gpm
o	Flow regulator	2.25 gpm
o	Pressure reducer output	2000 psi at 0 to 2.25 gpm

SYSTEM EVALUATIONS

EVALUATION SUMMARY

Table 15 is a summary of the evaluations that were performed on the three hydraulic flight-control systems. Table 16 provides comparable information for the three hoist systems. Both of the improved systems showed large gains over the baseline system in all areas except weight and cost. These results are not surprising, since the baseline system was designed in an era when low weight and cost were extremely intense design targets, while reliability and maintainability played much lesser roles. The VHP system showed superior characteristics in weight reduction and in (reduced) vulnerability. The ACP system was marginally superior to the VHP system in safety.

RELIABILITY EVALUATION

Table 17 provides a summary of the three hydraulic flight-control system quantitative reliability evaluations that were performed. Table 18 provides similar information for the three hoist systems. All rates were calculated via the process mentioned in the evaluation methodology section of this report.

Both the ACP and VHP systems showed impressive reliability improvements. Some of the improvement resulted from altering the basic system arrangement, rather than any inherent advantage of the technology involved. Moving the No. 1 and No. 2 flight-control pumps off the APU-driven AGB and onto the rotor transmission significantly reduced flight control system component wear because Boeing Vertol studies have shown that CH-47 APU's operate 1.7 hr. per helicopter FH. The ACP and VHP flight-control systems operate an estimated 58% of the time the baseline system operates.

The single most significant technology-oriented reliability improvement was the reduction in system leakage. The ACP and VHP systems both incorporate a degree of modularization and use swaged plumbing. These design features account for an estimated 85% reduction in system leak points.

For the purposes of this evaluation, the VHP system was assumed to be at a mature state of development and in use on fixed-wing aircraft. Since helicopter flight-control actuator seals operate under more rigorous conditions, it was further assumed that particular attention would have been directed to seal development in preparation for VHP use on helicopters. For this reason, VHP seals were assigned the same reliability rates as 3000 psi seals. The use of titanium fittings is not uncommon in

TABLE 15. FLIGHT-CONTROL SYSTEM EVALUATION SUMMARY

	Baseline system	ACP system	VHP system
Reliability	$\frac{29.462 \text{ Failures}}{10^3 \text{ FH}}$	43% better	43% better
Maintainability	$\frac{87.834 \text{ MMH}}{10^3 \text{ FH}}$	30% better	29% better
Safety	$\lambda = 2.0172326$	99% better	99% better
Vulnerability	2.45ft^2 ESVA[a]	37% better	48% better
Cost $\frac{\text{development}}{\text{manufacturing}}$	$\frac{1.0}{1.0}$	$\frac{10\% \text{ costlier}}{20\% \text{ costlier}}$	$\frac{20\% \text{ costlier}}{10\% \text{ costlier}}$
Weight	537.7 lbs	11% heavier	1% lighter

a = Equivalent Singly Vulnerable Area

TABLE 16. RESCUE HOIST SYSTEM EVALUATION SUMMARY

	Baseline system	ACP system	VHP system
Reliability	$\frac{3.599 \text{ failures}}{10^3 \text{ FH}}$	29% better	no change
Maintainability	$\frac{4.696 \text{ MMH}}{10^3 \text{ FH}}$	41% better	no change
Safety	Rescue hoist system does not affect aircraft flight safety. Personnel safety discussed in text.		
Vulnerability	Rescue hoist system does not affect vulnerability, since it is separate from the flight control system.		
Cost	1.0	7% costlier	20% costlier
Weight	28.6 lb	1% heavier	27% lighter

TABLE 17. FAILURE RATE DATA

COMPONENTS	BASELINE SYSTEM			ACP SYSTEM			VHP SYSTEM		
	NO. PER A/C	FAILURES/10^3 HR		NO. PER A/C	FAILURES/10^3 HR		NO. PER A/C	FAILURES/10^3 HR	
Pump	2		1.204	2		0.722	2		0.722
Power Module			3.408			2.502			1.644
Check Valves	6	0.120		16	0.224		14	0.196	
Relief Valves	2	0.040		2	0.003		6	0.084	
Filter (Ret.)	2	0.562		2	0.394		2	0.394	
Accumulator	2	1.300		2	0.910				
Manifold	2	0.020		2	0.014		2	0.014	
Filter (Press.)	2	0.562		2	0.394		2	0.394	
S. O. Valve	2	0.804		2	0.563		2	0.562	
Reservoir	2		0.010	2		0.009	2		0.009
Heat Exchanger				2		0.557	2		0.557
Sensors			0.802			1.506			1.771
Press. Switch	2	0.402		2	0.241		2	0.241	
Press. Trans	2	0.400		2	0.240		2	0.240	
ΔP Switch				6	0.724		6	0.724	
Temp Switch				2	0.265		4	0.530	
Level Trans				2	0.036		2	0.036	
							2		
Power Trans Unit				2		1.860			1.860
Actuators			10.331			5.312			5.674
Upper Sw Vel.	2	1.934		2	1.160		2	1.380	
Upper Pivot	2	2.064		2	1.238		2	1.380	
Lower Boost	4	2.412							
SAS	3	3.921							
Int. Lower Cont.									
Manifold				2	0.060		2	0.060	
Stick Boost				4	1.162		4	1.162	
SAS				3	1.692		3	1.692	
Lower Cont. Module			1.526			0.544			0.819
Filters	2	0.562							
S. O. Valve	2	0.804		2	0.482		2	0.482	
Check Valve	2	0.040							
Press. Reducer	2	0.120		2	0.072		2	0.072	
Temp. Switch							2	0.265	
Lines			5.250			2.555			2.555
Miscellaneous			2.931			1.144			1.144
Filter (Press.)	2	0.562							
Check Valves	8	0.160		8	0.128		8	0.128	
Hardware		1.876			0.750			0.750	
Servicing and Other	1	0.333			0.266			0.266	
TOTAL			29.462			16.721			16.755

third-generation hydraulic systems, such as the YUH-61A; but the VHP system uses titanium for both fittings and tubes. This practice is common in high-performance fixed-wing aircraft, but not in helicopters. There was some concern that titanium tubing might not withstand the rigors of Army helicopter vibration and maintenance environments, but no such reliability degradation could be proven while working within the scope of this study.

The preliminary design of a VHP CH-47C rotor-control actuator was accomplished during this program; Appendix A provides a description. Actuator stiffness was calculated in Reference 42. There was a 27% reduction in the static stiffness of the VHP actuator; that decreased stiffness is expected to reduce actuator reliability by 25% because of increased seal wear. The effect of actuator stiffness on total system stiffness was negligible. The decreased stiffness and reliability is not necessarily a VHP trait. Were the VHP actuator not a direct replacement for a unit used in the baseline helicopter, it could have been designed with a stiffness value that did not degrade reliability. This would have required a different helicopter rotor-control system geometry to allow for a VHP actuator that was shorter, with a larger fluid column diameter than the VHP unit described in Appendix A.

The VHP and ACP actuator reliability differences were caused by two factors: (1) change in the actuator stiffness, the VHP actuator degraded by 25%; and (2) a change in side loading on the rod and piston seals, with the VHP actuator improved by 10%. The reduced side loading was a result of the VHP actuator barrels having 4.0 inches centerline spacing, versus 4.5 inches for the ACP actuator. The net difference is a 15% reduction in VHP actuator reliability.

The VHP actuator has fewer total seals compared to the baseline actuator, but it has one more external dynamic seal. These factors had little impact on overall reliability. The VHP actuator seals were distributed as follows:

Seals	Baseline	VHP
External Dynamic		
High Pressure	0	0
Low Pressure	3	4

Seals	Baseline	VHP
Internal Dynamic	3	3
External Static	9	9
Internal Static	11	8
TOTAL	26	24

The VHP hoist system configuration was identical to the baseline system; no attempt was made to modularize the VHP system. Table 18 shows no improvement in VHP hoist system reliability when compared to the baseline, while the modularized ACP system improved by 27%. Differences in basic configuration, between the ACP and VHP hoist systems, prohibit making any direct reliability comparisons.

MAINTAINABILITY EVALUATION

Quantitative maintainability data is presented in Tables 19 through 21 for the three hydraulic flight control systems. Tables 22 and 23 provide similar information for the hoist systems. Maintainability evaluation techniques were discussed in the Evaluation Methodology section of this report.

The ACP and VHP flight control systems both show improvement over the baseline system. There were a number of influencing factors, the most predominant being the improved reliability of both systems. Maintainability improvements were not proportional to reliability improvements, chiefly because significant portions of the reliability improvements were based on having fewer plumbing problems with the ACP and VHP systems. Since relatively low maintenance task times are associated with correcting plumbing problems, the maintainability benefits are less.

The manifold/cartridge configurations of the ACP and VHP systems resulted in lower task times for component replacement. Fault isolation times were also slightly reduced, but not to the level that could have been realized had whole modules been quickly replaceable.

The VHP hoist design was a direct replacement for the baseline system and so it had the same maintainability, as well as reliability, characteristics of the baseline system. Modularizing the ACP hoist system greatly improved its maintainability. In addition, the ACP hydraulic winch motor was moved to a fixed boom outside the cabin and covered with a fairing; this provided gains in:

TABLE 19. MAINTAINABILITY EVALUATION OF BASELINE FLIGHT-CONTROL SYSTEM

COMPONENT	NO. PER AIRCRAFT	MMH PER TASK	TASK FREQ 10^3 FH	MMH/10^3 FH PER A/C
CORRECTIVE MAINTENANCE				
Pump	2	0.780	1.204	0.936
Power Control	2	0.333	3.408	1.135
Reservoir	2	0.670	0.010	0.007
Heat Exchanger	0	-	-	-
Sensors	4	0.300	0.802	0.241
Power Transfer Unit	0	-	-	-
Swiveling Actuator	2	3.350	1.934	6.479
Pivoting Actuator	2	3.400	2.064	7.018
Lower Boost Actuators	4	0.980	2.412	2.364
SAS Actuators	2	2.550	3.921	9.999
Lower Pressure Control	2	0.500	1.886	0.943
Lines	-	0.250	9.250	2.313
Miscellaneous	-	0.250	2.931	0.733
Fault Isolation (30%)	-	-	-	9.650
	Corrective Maintenance Total			41.818
PREVENTIVE MAINTENANCE				
Service Filter Element	8	0.220	12.800	2.816
Service System Fluid	2	0.160	25.000	8.000
Daily Inspection	-	0.100	250.000	25.000
Intermediate Inspection	-	0.240	20.000	4.500
Periodic Inspection	-	0.540	10.000	5.400
	Preventive Maintenance Total			46.016
Baseline Flight-Control System Total (Corrective + Preventive)				87.834

TABLE 20. MAINTAINABILITY EVALUATION OF ACP FLIGHT-CONTROL SYSTEM

Component	No. Per Aircraft	MMH Per Task	Task Freq Per 10^3 FH	MMH Per 10^3 FH
Corrective Maintenance				
Pump	2	0.400	0.722	0.289
Power Module	2	0.200	2.502	0.500
Reservoir	2	0.670	0.009	0.006
Heat Exchanger	2	0.670	0.557	0.373
Sensors	14	0.200	1.506	0.301
PTU	2	0.250	1.860	0.465
Swiveling Actuator	2	3.350	1.160	3.886
Pivoting Actuator	2	3.400	1.238	4.209
Integrated Lower Actuator	4	1.230	2.914	3.584
Lower Control Module	2	0.300	0.554	0.166
Lines	-	0.250	2.555	0.639
Misc.	-	0.250	1.144	0.285
Fault Isolation (27%)	-	-	-	3.970
				18.673
Preventive Maintenance				
Service Filter Element	4	0.280	6.400	1.792
Service System Fluid	2	0.040	50.000	2.000
Daily Inspection	-	0.120	250.000	30.000
Intermediate Inspection	-	0.210	20.000	4.200
Periodic Inspection	-	0.460	10.000	4.600
				42.592
ACP Flight-Control System Total (Corrective and Preventive)				61.265

TABLE 21. MAINTAINABILITY EVALUATION OF VHP FLIGHT-CONTROL SYSTEM

Component	No. per aircraft	MMH per task	Task Freq 10^3 FH	MMH per 10^3 FH
CORRECTIVE MAINTENANCE				
Pump	2	0.400	0.722	.289
Power Module	2	0.200	1.644	.329
Reservoir	2	0.670	0.009	.006
Heat Exchanger	2	0.670	0.557	.373
Sensors	16	0.200	1.771	.354
PTU	2	0.250	1.860	.465
Swivelling Actuator	2	3.350	1.380	4.623
Pivoting Actuator	2	3.400	1.380	4.692
Integrated Lower Actuator	4	1.230	2.914	3.584
Lower Control Module	2	0.300	.819	.246
Lines	-	0.250	2.555	.639
Miscellaneous	-	0.250	1.144	.286
Fault Isolation (27%)	-	-----	-----	4.289
	CORRECTIVE MAINTENANCE TOTAL			20.175
PREVENTIVE MAINTENANCE				
Service Filter Element	4	0.28	6.400	1.792
Service System Fluid	2	0.04	50.000	2.000
Daily Inspection	-	0.12	250.000	30.000
Intermediate Inspection	-	0.21	20.000	4.200
Periodic Inspection	-	0.46	10.000	4.600
	PREVENTIVE MAINTENANCE TOTAL			42.592
VHP Flight-Control System Total (Corrective + Preventive)				62.767

TABLE 22. MAINTAINABILITY EVALUATION OF BASELINE AND VHP RESCUE HOIST SYSTEMS

Component	No. Per Aircraft	MMH per Task	Task Freq per 10^3 FH	MMH per 10^3 FH
CORRECTIVE MAINTENANCE				
Winch Motor	1	0.430	0.201	0.086
Hoist Control Valve	1	0.680	1.407	0.957
Brake and Power Valve	1	0.800	0.603	0.482
Relief Valve	1	0.410	0.020	0.008
Flow Regulator Valve	2	0.410	0.040	0.016
Check Valve	1	0.410	0.020	0.008
Lines	-	0.380	1.749	0.665
Hoist Operator's Panel	1	0.250	0.100	0.025
Fault Isolation (20%)	-	---	---	0.449
				2.696
PREVENTIVE MAINTENANCE				
Daily Inspection	-	---	---	---
Intermediate Inspection	-	---	---	---
Periodic Inspection	-	0.200	10.000	2.000
BASELINE AND VHP SYSTEM TOTALS (CORRECTIVE + PREVENTIVE)				4.696

TABLE 23. MAINTAINABILITY EVALUATION OF ACP RESCUE HOIST SYSTEM

Component	No. Per Aircraft	MMH per Task	Task Freq. per 10^3 FH	MMH per 10^3 FH
CORRECTIVE MAINTENANCE				
Winch Motor	1	0.750	0.201	0.151
Brake and Power Valve	1	0.800	0.055	0.040
Priority Valve	1	0.410	0.030	0.012
Hoist Control Module	1	0.380	1.320	0.502
Hoist Operator's Panel	1	0.250	0.100	0.025
Fault Isolation (20%)	-			0.146
				0.876
PREVENTIVE MAINTENANCE TOTAL				
Daily Inspection	-	---	---	---
Intermediate Inspection	-	---	---	---
Periodic Inspection	-	1.900	10.000	1.900
ACP SYSTEM TOTAL (CORRECTIVE + PREVENTIVE)				2.776

1. Mechanical Reliability - the improved system provided less complexity.

2. Personnel Safety - the configuration eliminated a requirement to rig cables before using the hoist and therefore eliminated potential for error.

3. Operational Ease and Convenience - the crew members were not required to rig cables, and the permanent boom provided for easier transitioning of hoist loads into the cabin.

The increase in airframe drag is considered minor compared to the benefits listed above.

Unfortunately, none of these advantages show up in the hydraulics-oriented rating methodology that was established for this study. But the deteriorated winch motor accessibility appears in both the corrective and the preventive maintenance tasks related to the motor. Motor replacement time is high, and the periodic inspection time shown would have been even lower except for motor accessibility.

SAFETY EVALUATION

Table 24 provides component FSR rates for the three flight-control systems. Figures 28, 29, and 30 are the FSR diagrams for the same systems. FSR was defined in the Evaluation Methodology section of this report.

The ACP and VHP systems have safety improvements in several areas.

1. Both hydraulic pumps no longer share the same mechanical drive system, and the FSR analysis shows a major safety improvement for this action. However, it must be noted that no instance of inflight pump drive dual failures have been recorded for the CH-47 series.

2. Fewer precautionary landings are expected as a result of a two-thirds reduction in leak points for both systems.

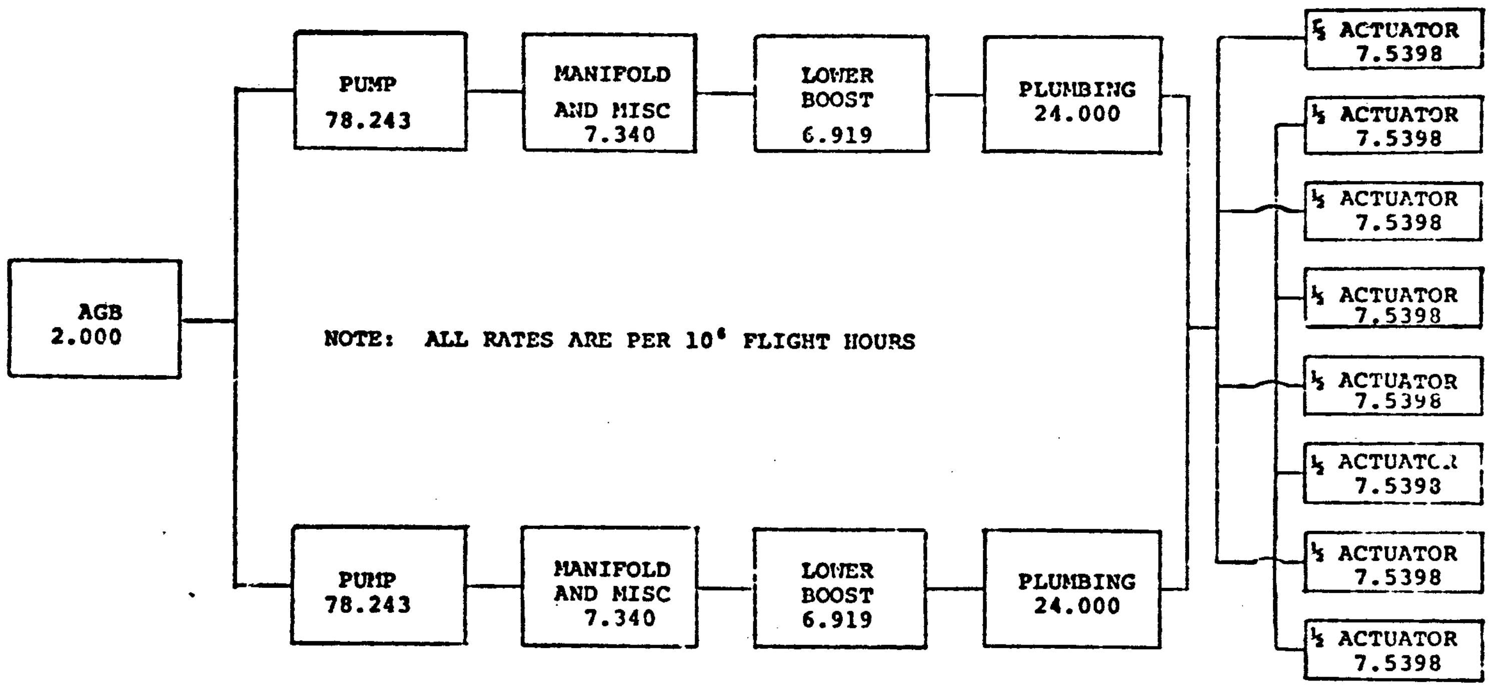
3. Reliability improvements resulted in an overall increase in FSR.

The two advanced systems include other improvements that will enhance safety. These are lesser, but still significant, improvements.

TABLE 24. COMPONENT FSR FAILURE RATES*

	Baseline system failure rate per 10^6 FH	ACP system failure rate per 10^6 FH	VHP system failure rate per 10^6 FH
Accessory Gearbox	2.0	-	-
Pump	86.74	78.243	78.243
Reservoir	0.2	0.2	0.2
Accumulator	0.2	0.2	-
Pressure Reducer	2.113	2.100	2.103
Tubing, Hoses, Fittings	24.0	3.494	3.494
Actuator, Lower Boost	4.206	3.575	3.575
Actuator, Swiveling	2(7.5398)	2(7.5398)	2(9.5733)
Actuator, Pivoting	2(7.5398)	2(7.5398)	2(9.5733)
Filter	0.6	0.2	0.2
Manifold/Module/Elements	6.340	5.220	5.220

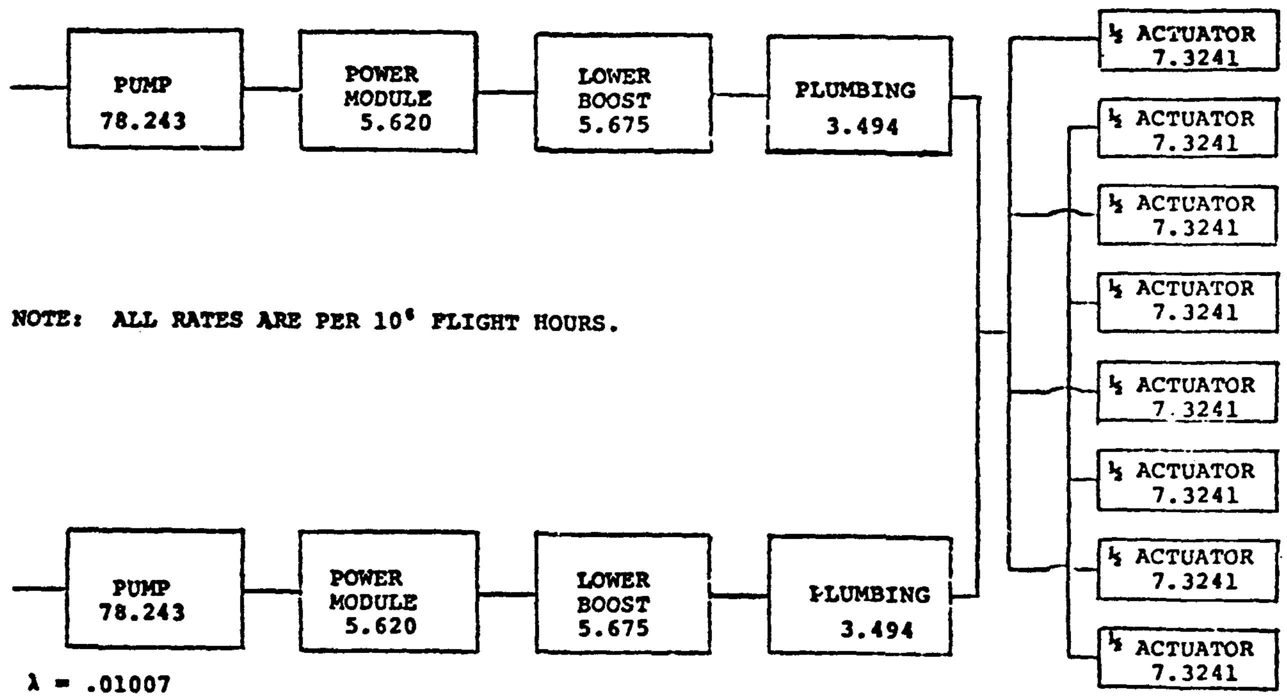
*The procedure described in the Evaluation Methodology section must be used to determine system flight safety reliability.



$\lambda = 2.0172326$

FLIGHT SAFETY RELIABILITY FOR A ONE HOUR MISSION = .99999798277

Figure 28. Baseline System FSR.

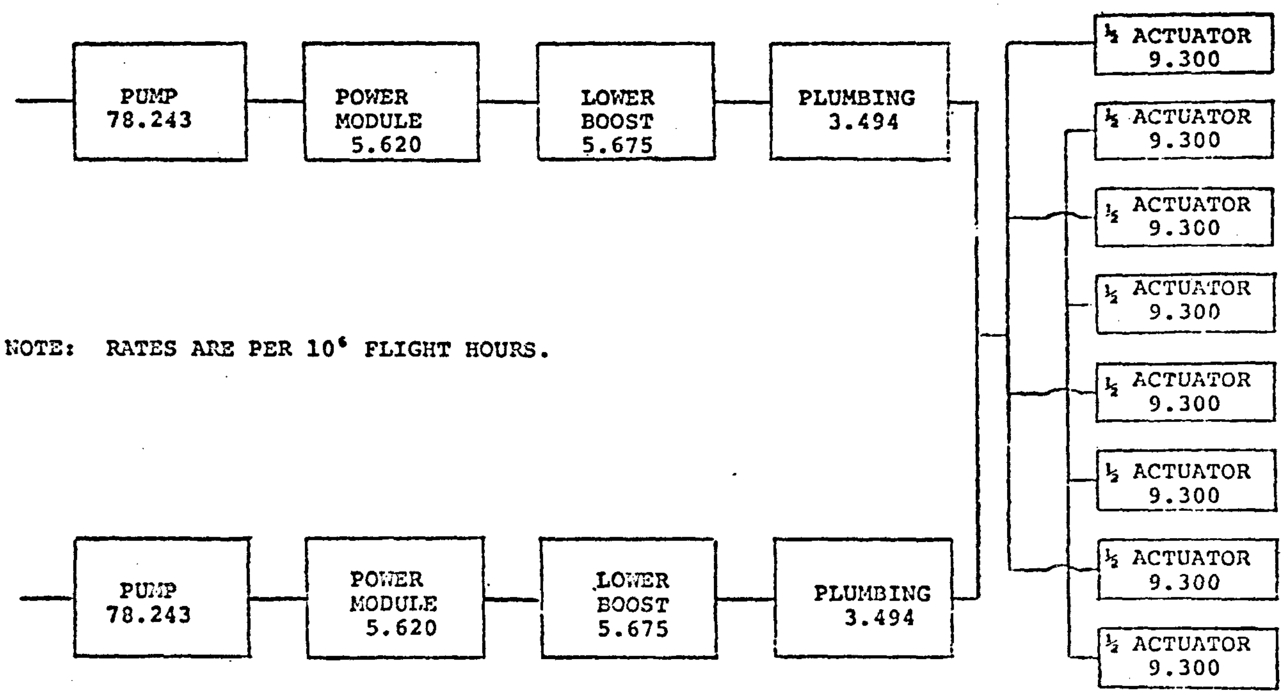


NOTE: ALL RATES ARE PER 10^6 FLIGHT HOURS.

λ = .01007

FLIGHT SAFETY RELIABILITY FOR A ONE HOUR MISSION = .99999998993

Figure 29. ACP System FSR.



NOTE: RATES ARE PER 10^6 FLIGHT HOURS.

$\lambda = .01028$

FLIGHT SAFETY RELIABILITY FOR A ONE HOUR MISSION = .99999998962

Figure 30. VHP System FSR.

1. The possibility of a "Murphy" condition has been reduced or perhaps eliminated by the use of Rosan fittings, different port sizes, increased tube spacing, and modularization. There are recorded instances of CH-47 hydraulic lines being inadvertently crossed. At least one, and perhaps two, cases resulted in major mishaps.

2. Nearly all flight control-hydraulic lines and components have been removed from the aft cabin area; only the one pump and its connecting lines remain. For an actual production program, the utility hydraulic system should also be redesigned since it has even more lines located in the aft cabin area than the baseline flight control system.

VHP system safety was slightly inferior to that of the ACP system. This was a result of the VHP rotor control actuator design having a higher malfunction rate because of reduced stiffness as explained in the Reliability Evaluation section.

Personnel safety is an issue that is not clearly defined. Tests have shown that VHP pinhole leaks produce a very concentrated stream of fluid for the first inch, and at approximately 6 inches the stream turns into a fine mist (Reference 27). This does not appear to present a safety hazard appreciably different from 3000-psi systems. The intent of the test was to investigate VHP potential for inducing structural damage rather than personnel safety so firm conclusions cannot be formed. A check of USAAAVS records from 1970 to the present revealed no instances of injuries due to 1500- or 3000-psi hydraulic system leaks.

The rescue hoist system has no impact on FSR since the system is hydraulically isolated from the flight-control hydraulic system, but it does affect personnel safety. The baseline and VHP systems require that the winch cable be rigged between the winch drum and the cable exit point in the fuselage before the hoist can be operated. This could allow human error to affect the safety of the hoist operator and personnel being hoisted. The ACP system eliminated this potential problem by moving the winch and winch motor to a fixed, external boom.

VULNERABILITY EVALUATION

Summary

Quantitative vulnerability evaluations were performed using the procedures, data, and tables provided in the Evaluation Methodology section of this report. The results were as follows:

System	Vulnerability (ESVA), ft^2	
CH-47C	2.45	Baseline
ACP	1.55	37% Reduction
VHP	1.27	48% Reduction

A threat scenario, for a composite fleet, was then generated based on the 1.4×10^6 flight hours accumulated by the CH-47 fleet up to May 1976. The aircraft damaged and destroyed rates due to combat for each of the evaluated hydraulic systems were directly proportional to the ESVA variations of the systems.

Baseline System Vulnerability

The projected area of CH-47C flight-control hydraulic system components, plus the fuselage projected area, were previously generated under Contract DA 44-177-AMC-436(T) "Flight Controls Survivability". The average helicopter fuselage projected area was 350 ft^2. Each hydraulic system had a projected area of 7.33 ft^2 for power generation and distribution components, and 4.00 ft^2 for flight-control actuators.

The flight-control actuators are singly vulnerable. From Reference 41, actuator vulnerable area is calculated as follows for a threat of 10 7.62mm rounds:

Presented area	=	4.00 ft^2
Shielding efficiency	=	75%
Probability of killing both systems of a redundant pair of vulnerable systems having total vulnerable area (AV) (P_K)	=	0.60

Vulnerable area = (presented area) (1 - Shielding efficiency) (P_K)

Vulnerable area = (4.0) (.25) (.60) = 0.60 ft^2

An equivalent singly vulnerable area (ESVA) of 0.80 ft^2 for the power and distribution section can then be determined using Figures 14 and 15.

Vulnerability due to inadequate line spacing must be added to the above ESVA. Reference 41 provided the following:

Line Spacing C_L to C_L	P_K	Percent CH-47C at Spacing	ESVA For System - sq ft (From Figure 16)
.50	.494	5.2	.188
1.00	.304	24.5	.546
2.00	.107	13.0	.102
4.00	.050	57.3	.210
8.00	.034	----	--
12.00	.030	----	---
Total			1.046 ft^2

The total baseline system ESVA can now be calculated by adding inadequate line spacing ESVA to the power generation and distribution ESVA and the actuator vulnerable area.

Element	Vulnerability (ESVA), ft^2)
Flight-control actuators	0.60
Power generation and distribution	0.80
Inadequate line spacing	1.05
	2.45

ACP System Vulnerability

ACP system actuator size and vulnerability characteristics are similar to the baseline system. Therefore, the same vulnerable area estimate will be used.

ACP power generation and control elements have a projected area of 5.86 ft^2. This is 20% less than the baseline system, and results primarily from modularizing the system. An ESVA of 0.63 ft^2 for this portion of the ACP system is obtained using Figures 13 and 14.

ACP system line spacing has been kept to a minimum of 12 inches. Using Figure 15, the ESVA due to inadequate line spacing is determined to be 0.32 ft^2.

The total ACP system ESVA can now be calculated by the method that was used for the baseline system:

Element	Vulnerability (ESVA, ft^2)
Flight-control actuators	0.60
Power generation and distribution	0.63
Inadequate line spacing	0.32
	1.55

VHP System Vulnerability

VHP system actuator size and vulnerability characteristics are very similar to the ACP and baseline systems. Therefore, the same actuator vulnerable area will be assumed.

Reference 43 determined that VHP power generation, and control elements have a projected area of 3.93 ft^2. An ESVA of 0.35 ft^2 for this portion of the VHP system can now be obtained using Figures 13 and 14.

VHP system line spacing, like the ACP system, has been kept to 12 inches or more. Therefore its ESVA is 0.32 ft^2, the same as that of the ACP system.

The total VHP system ESVA can now be determined:

Element	Vulnerability (ESVA, ft^2)
Flight-control actuators	0.60
Power generation and distribution	0.35
Inadequate line spacing	0.32
	1.27

Threat Scenario

Threat scenarios were generated after reviewing new helicopter ROC (Required Operational Characteristics) documents. Currently, major Army development efforts are under way across the total helicopter class spectrum, from light observation to the heavy lift mission. Threat data in requested for proposal (RFP) requirements for the following helicopters were reviewed:

- Utility Tactical Transport Aircraft System (UTTAS)
- Advanced Attack Helicopter (AAH)
- Advanced Scout Helicopter (ASH)
- Heavy Lift Helicopter (HLH)
- Aircraft Survivability Equipment (CH-47C ASE)
- YCH-47D

All of these systems are programmed for missions in low and high intensity conflicts. Based on stated design requirements as well as historical combat data, the following criteria was established for this evaluation:

1. Type of weapons
   - 7.62mm small arms
   - 12.7mm small arms
   - 23mm HEI-T anti-aircraft artillery
2. Hit density
   - Small arms - 10 hits
   - AAA - 1 hit
3. Number of encounters
   - One 10-hit small arms encounter per 500 FH of combat operation
   - One single-hit AAA encounter per 5000 FH of combat operation
4. Loss criteria
   - Assume 50% of forced landings are not recovered
5. Combat operations time
   - Assume 50% of fleet hours are flown in combat. This is based on actual CH-47 experience.

The calculated ESVA of each hydraulic system and the kill probability from Figure 14 for total vulnerable area were then used to determine probable combat losses in the defined threat situation.

Hydraulic System	Forced Landings	Attrition *
Baseline	26	14
ACP	18	10
VHP	14	7

*It was assumed that 50% of the kills were recovered, and 50% attrited.

LCC savings that could be accredited to the ACP and VHP systems if the attrited aircraft required replacement would be approximately $3 million for each CH-47D.

Conclusions

The vulnerability characteristics of both advanced systems were substantially better than those of the baseline system. The greatest improvement was in the area of line spacing, where the baseline system has 4 inches or less spacing versus 12 inches for the ACP and VHP systems. Many VHP lines were a size smaller than the ACP, but this did not prove to be an advantage. The small differences in line diameter were negligible when compared to the potentially damaging swath of a tumbling 7.62mm projectile.

VHP power-generation and control elements have a projected area that is 46% less than the baseline system and 33% less than the ACP system. The 33% reduction resulted from the ability to make 8000-psi components smaller than 3000-psi components.

Secondary vulnerability improvements were obtained by both advanced systems through modularizing the many scattered elements that are in the power-generation and control section of the baseline system. The VHP system had the added advantage of having no accumulators in the VHP system, but the lack of accumulators reflected design team preferences rather than any VHP/ACP technology differences.

VOLUME EVALUATION

Component envelopes were not a significant factor in any of the three systems. It had some impact on the vulnerability issue, and was discussed in that evaluation. The state-of-the-art section of this report discussed the influence of component envelopes on helicopter design and noted that it had relatively little impact. Component volume would have been an issue if an advanced concept, such as IAP, had been selected as one of the advanced designs.

COST EVALUATION

Cost comparisons of the three flight control hydraulic systems are shown in Table 25. Table 26 provides similar information for the three hoist systems. As noted in the Evaluation Methodology section of this report, the VHP system was assumed to be beyond its basic development period and so did not suffer the cost penalties normally associated with new technology.

The baseline system was approximately 20% less costly than the ACP and VHP systems in design/development and manufacturing costs. Operational costs were not evaluated, but there is no doubt that the superior reliability, maintainability, safety, and survivability characteristics of the two advanced systems would cause their life-cycle costs to be substantially less than that of the baseline.

Manufacturing costs show the VHP system with a slight advantage over the ACP system. This advantage is based primarily on the ground rule that, given comparable functions, such as machining requirements, the smaller unit will be less expensive. This assumes that VHP pumps and seals will impose no peculiar machining or installation requirements.

A general conclusion can be drawn concerning VHP systems costs. After refinement, VHP systems should be marginally lower in cost than ACP systems. Basic system configuration and features will be the main determinants of development and manufacturing costs. The degree of reliability, maintainability, safety, and vulnerability that is designed into those systems, along with spares provisioning policies, will have a greater effect on life-cycle costs than the system pressure level.

The ACP system has a distinct advantage in the area of GSE cost, because 3000-psi GSE has been extensively developed; it is plentiful in the supply system and at many airfields. This aspect was not weighted in the maintainability evaluation, because it was assumed that some GSE would have been previously

TABLE 25. HYDRAULIC FLIGHT-CONTROL SYSTEM COST RATINGS

COMPONENT	*ACP	*VHP	REMARKS
DESIGN/DEVELOPMENT			
Actuators	6	7	- Both have rip-stop construction - VHP actuator has one more rod seal
Pumps	5	6	- Assumes no new technology required for VHP - Higher cost based on less familiarity with VHP
Tubing	5	5	- No new technology required
Reservoir Module	6	6	- Both modularized - Both have additional components
MANUFACTURING			
Actuators	7	6	- VHP actuator smaller, has less material - VHP machining operations same as ACP - ACP & VHP have rip-stop construction
Pump	5	4	- VHP pump smaller due to lower CIPR
Tubing	5	6	- Both have less tubing than baseline - Both use advanced fittings - Titanium tubing costs more than stainless steel
Reservoir Module	7	6	- Both have additional components - VHP module smaller, has less material

*Baseline CH-47C assumed to have a rating of 5.

TABLE 26. RESCUE HOIST HYDRAULIC SYSTEM MANUFACTURING COST

COMPONENT	*ACP	*VHP	REMARKS
Winch Motor	5	6	- ACP comparable to baseline - VHP unfamiliar to suppliers
Control Valves	6	6	- ACP is modularized - VHP unfamiliar to suppliers
Plumbing	5	6	- ACP has less plumbing due to modularization but uses advanced fittings - VHP uses titanium lines and fittings

developed for the VHP fixed-wing aircraft that were in service. Initially at least, VHP GSE costs would be higher and availability would be limited. It should be noted, however, that the recent trend in Army helicopters of the utility class and larger has been to design more onboard hydraulic ground power capability and to rely less on GSE.

WEIGHT EVALUATION

Summary

The adjusted weights for the three hydraulic flight-control systems are listed below:

CH-47C	537.7 lb	(baseline)
ACP	594.0 lb	(11% heavier)
VHP	530.4 lb	(1% lighter)

The VHP system was nearly 11% lighter than the ACP system. System weight details are shown in Table 27. The VHP system used titanium tubing and did not include accumulators. The baseline and ACP systems used steel tubing and had accumulators. These design options are related to designer preferences rather than technology differences. Therefore, 7.4 lb were added to the VHP system for 2 accumulators and 5.0 lb for the difference in tubing weights. These adjustments allow a more accurate comparison of technology differences.

General

Both of the advanced systems incorporated features that were not in the baseline. These included additional temperature and fluid-level sensors plus central-point reservicing. These features would have added approximately nine lb to the baseline system weight, and changed the weight differentials by nearly 2%.

Both advanced systems removed the flight-control hydraulic pumps from the AGB, relocating one on the forward rotor transmission and one directly on the aft rotor transmission. This was done primarily to improve safety and reliability. There were some weight savings related to the change. Pump electrical depressurization valves were no longer required, so even the ACP system shows a reduced pump weight in Table 27. According to the table, these savings in pump weight were more than cancelled by the PTU's the new concept required. But Table 27 does not include drive system weight savings that would result because the AGB could be reduced in size and weight. The AGB weight reduction would have more than offset the added PTU weights.

TABLE 27. FLIGHT-CONTROL SYSTEM WEIGHT COMPARISON

	BASELINE SYSTEM					ACP SYSTEM					VHP SYSTEM				
	COMPONENTS	FLUID	FITTINGS	SUPPTS & HDW	TOTAL	COMPONENTS	FLUID	FITTINGS	SUPPTS & HDW	TOTAL	COMPONENTS	FLUID	FITTINGS	SUPPTS & HDW	TOTAL
Pumps	(2) 26.8	0.5		0.1	27.4	17.8	0.5		0.1	18.4	(2) 13.6	0.3		0.1	14.0
Reservoirs	(2) 7.4	18.0			25.4	PCM					RPM				
Accumulators	(2) 7.0	0.4			7.4	PCM					N/A				
Heat Exchangers	N/A					PCM									
Filters - 3/8 T.S.	(2) 3.2	0.5		0.9	4.6	PCM					RPM				
Return	(2) 11.0	3.2		2.5	16.7						RPM				
St. Bat & SAS	(2) 2.5				2.5						N/A				
Valves															
Relief				0.2	0.2						RPM				
Check	0.6				0.6	0.3				0.3					
Press. Red.	(2) 1.5				1.5						LCM				
SAS Shut-off	(2) 1.7	0.1			1.8	LCM					LCM				
Reservoir Pwr Mod	N/A					(2) 90.8	23.0		5.0	118.8	(2) 78.0	14.2		3.9	96.1
Fill Module	N/A					5.0				5.0	5.0				5.0
Lwr Control Mod.	N/A					(2) 5.0	0.1		0.2	5.3	(2) 5.2	0.1		0.2	5.5
Manifold - Power	(2) 6.1	0.2		0.9	7.2	(1) 7.0	0.2			7.2					
- Dual St. Bat											7.0	0.2			7.2
Controls - Circuitry & SW	3.2				3.2	3.2				3.2	5.0				5.0
- Bleed Air	4.6				4.6	4.6				4.6	N/A				
Actuators - Upper Controls	(4) 194.6	8.4		38.1	241.1	220.9	8.4		38.7	268.0	187.7	2.9		38.1	228.7
Stick Bat	(4) 28.0	1.2		4.8	34.0						N/A				
SAS	(3) 33.3	0.9		0.3	34.5						N/A				
SAS/Bat Pkg						79.7	1.2		3.5	84.4	79.7	1.2		3.5	84.4
Plumbing - Fwd F.C.	9.8	2.1	2.9	0.8	15.6	8.3	1.8	2.6	0.7	13.4	6.1	1.3	1.8	0.7	9.9
Fwd SAS	4.9	0.4	1.1	0.1	6.5	1.5	0.1	0.5		2.1	1.5	0.2	0.5	0.5	2.7
Mid	14.3	3.6	2.5	2.0	22.4	8.8	2.5	0.8	1.6	13.7	10.3	2.9	1.3	4.1	18.6
Aft	36.4	10.7	17.2	2.9	67.2	14.0	4.0	5.0	1.2	24.2	6.5	1.3	1.8	1.0	10.6
Added Util	N/A										1.4	0.5	1.4	0.3	3.6
Power Trans. Unit	N/A					(2) 13.4			2.0	15.4	17.4	0.2		1.6	19.2
Misc Supports & Hardware				13.3	13.3				10.0	10.0				7.5	7.5
TOTALS	396.9	50.2	23.7	66.9	537.7	490.3	41.3	8.9	63.0	594.0	414.8	24.9	5.9	60.5	518.0

Baseline System Weight

The CH-47C was designed with weight as an extremely intense consideration, and the hydraulic flight-control system reflects this attitude. The total weight of the hydraulic flight control system is less than 3% of the helicopter empty weight.

ACP System Weight

The ACP hydraulic flight-control system weighs 56.3 lb more than the baseline. Modularizing system components added 50 lb and forced the need for heat exchangers, which added another 21.6 lb. But modularization eliminated many tubes, hoses, and supports; this, combined with the employment of Rosan fittings and swaged tubing, reduced system weight by 58.3 lb. The net result is a 13.3 lb weight penalty for modularization.

The PTU's added 15.4 lb to the system, but accounted for undetermined weight savings in the drive transmission and utility hydraulic systems. The savings are not included here because this evaluation covered only the flight-control hydraulic system.

The remaining 28.9 lb, of the total 56.3 lb ACP system weight disadvantage, is made up of miscellaneous items. These items include single point servicing equipment, diagnostics, and inflight monitoring sensors.

VHP System Weight

The VHP system was modularized, suffered the additional weight burden of heat exchangers and PTU's, yet still managed to be lighter than the baseline. The most significant VHP weight reduction (68.9 lb) was in plumbing, where the decreased flow rate at 8000 psi allowed the use of smaller line sizes.

Rescue Hoist System Weight

Hoist system weight differentials between the two advanced systems cannot be easily analyzed because of differences in basic system configuration. The VHP design team elected not to modularize the baseline system, while the ACP team modularized it and moved the hydraulic winch motor to a boom mounted outside of the aircraft. The ACP team decision improved reliability and personnel safety, but degraded maintainability and weight.

Table 28 shows a weight breakdown for each of the three hoist systems and notes the major areas of VHP weight savings. The VHP hoist design used titanium tubing, while the baseline and ACP designs used steel. The baseline and ACP systems could have saved some weight by also using titanium tubing.

TABLE 28. RESCUE HOIST SYSTEM WEIGHT SUMMARY

Item	ACP System, lb	Baseline System, lb	VHP System, lb	VHP Reductions From Baseline, %
Winch Motor	3.8	3.8	2.1	45
Valves:				
Flow regulator (2)		1.0	.74	
Hoist control		3.6	2.65	
Brake and power		1.7	1.25	
Relief		1.0	.74	29
Pressure reducer		0.8	0.59	
Check		0.2	0.1	
Module	9.8			
Panel, Hoist Operator	3.2	3.2	3.2	
Control Circuitry	3.4	3.4	3.4	
Plumbing:				
Lines, hoses	5.1	5.7	3.69	44
Fittings	1.8	2.0	0.59	
Fluid	0.9	1.0	0.60	40
Supports	0.4	0.6	0.60	
Miscellaneous Hardware	0.5	0.6	0.60	
TOTALS	28.9	28.6	20.85	27%

Weight Evaluation Conclusions

The VHP hydraulic flight-control system is marginally lighter than the baseline system, which is not competitive in terms of reliability, maintainability, safety, and vulnerability. More significantly, it is nearly 11% lighter than the ACP system, which has comparable features and incorporates modern 3000-psi technology. The VHP hoist system reduced baseline and ACP system weights by over 20%. This is an example of how 8000-psi technology weight benefits vary with system power requirements and configuration. The hoist was a "muscle" application, with 6-gpm flow rates throughout the entire system. The flight-control hydraulic system application required more sensitive control and had reduced flow requirements where the system branched to the lower controls and individual rotor-control actuators.

VHP ACTUATOR STABILITY ANALYSIS

Appendix A describes a VHP rotor-control actuator that was designed for the baseline helicopter. The appendix includes a stability analysis of the VHP actuator and compares the stiffness characteristics of the VHP design with the baseline design. Relating this data to previous actuator stability analyses and experience allows certain conclusions. A VHP design, if dynamic characteristics are controlled, can be as stable as today's 3000-psi designs. The stability analysis did not consider the critical valve damping and linkage spring rates which are dominant in the actuator's stability; however, the analysis does show a reasonable probability for success were those factors to be considered. Prior to actual VHP actuator development, it is recommended that further studies be initiated to determine the ability of the VHP design to maintain linear valve gain, controllable valve friction and viscous forces, and other stability-related parameters.

ACP SYSTEM BENEFITS AND DRAWBACKS

ACP system benefits are its mature state of technological development and familiarity to helicopter builders and operators. The ACP system performs its functions reasonably well, and off-the-shelf GSE and components are readily available. However, 3000-psi technology has reached a plateau in regard to weight reduction and, to a lesser degree, in reliability improvements. Potential exceptions to this are: (1) the development of high-speed pumps and motor; (2) the use of new materials that have high strength-to-weight ratios; and (3) improved actuator reliability, due to the use of new sealing configurations. Vulnerability technological advancements are anticipated during the next 20 years, but most of the improvements in safety and maintainability will be related to design execution.

ACP SYSTEM DEVELOPMENT REQUIREMENTS

The ACP System does not require extensive R&D effort as it uses the latest state-of-the-art technology. The Boeing Vertol YCH-47D, which is now under design, will incorporate a flight control hydraulic system that includes many features of the ACP system. The CH-47D is scheduled to be the standard Army MLH through the year 2000.

The ACP concepts of removable modules, or manifolds having replaceable cartridges, probably will be standard for U. S. Army helicopter flight control hydraulic systems through the next 20 years. Reconnaissance, utility, and attack helicopters are expected to have hydraulic systems that contain power generation and control elements in one or, perhaps, two quickly removable modules. The medium- and heavy-lift helicopters (MLH and HLH) in the cargo/transport category will probably require a minimum of two modules because of the complexity and module weight considerations. But HLH designers may elect to employ local power generation and control systems in order to eliminate long plumbing runs and/or keep module sizes within limits. Fly-by-wire systems, while not considered within the scope of this report, will effect the MLH and HLH, because the deletion of lower boost systems could result in fewer modules.

Some evolution should take place in diagnostics, since system complexity strains the capabilities of the average U. S. Army soldier-mechanic. Some of the new items will undoubtedly be spinoffs from diagnostics that are now being developed for other more critical systems. The worth of diagnostics is in its ability to pinpoint defective components that can be easily replaced. Logically then, future hydraulic systems must strike some balance between diagnostics and modularization. The simplest way to reduce fault isolation time is to modularize to the degree where every system element is contained in one easily removable unit. This is not feasible for various reasons, particularly cost and weight. The use of diagnostic equipment allows lesser degrees of system modularization without prohibitive fault-isolation time penalties. Future hydraulic system buyers and designers must weigh the summed cost of modularization and diagnostics against the penalties associated with inferior system fault-isolation characteristics. These penalties include increased parts procurement and stockage costs, decreased helicopter availability and mission reliability, as well as increased MMH costs. Presently, there is no suitable means to weigh and compare the costs associated with these penalties; future helicopter system design efforts must have the means to make these comparisons. The diagnostics/modularization issue may be the single most important determinant of Army helicopter hydraulic systems LCC during the next 20 years.

Maintainability, safety, and vulnerability all have potential for improvement via more careful attention to design details. The state-of-the-art section of this report listed some potential improvements. There may be basic technology developments in the area of vulnerability. The state-of-the-art section of this report discusses a number of concepts that are under development, and it is likely that there will be even more intensive efforts in this area.

Piston pumps, with their inherent advantages and problems, will continue as the primary power source during this period. It is possible that technological evolution may allow pumps and motors to operate at higher speeds and therefore be smaller and lighter, but these improvements may be traded for increased reliability. While no technology breakthroughs are expected to radically improve reliability, advancements should be made through different utilization of components that are available today. The recent emphasis on investigating the effects of contamination on hydraulic systems may lead to more than just the selection of acceptable contamination levels. It may provide for more effective control of contaminants, once a particular level is selected. The unvented cascaded seals discussed in Appendix C offer very real potential for reliability improvement.

VHP SYSTEM BENEFITS AND DRAWBACKS

VHP system benefits for Army helicopters lie in the areas of weight reduction and improved combat survivability. The VHP system drawbacks are that (1) helicopter manufacturers and operators are unfamiliar with 8000-psi technology; and (2) it does not provide weight-reduction benefits over the entire spectrum of Army helicopter hydraulic systems.

The VHP system was 18% less vulnerable than the ACP system and 48% less vulnerable than the baseline system. The smaller projected area of the VHP system was the single largest factor in its reduced vulnerability as compared to the ACP system. Major components, such as actuators, can be protected to some degree by other components, armor plating, or integral survivability features. But it is nearly impossible to effectively protect pumps, valves, and plumbing that are scattered throughout the aircraft.

VHP technology does not offer weight benefits to all classes of Army helicopters. Generally, 8000-psi systems begin to show weight reductions over comparable 3000-psi systems when the system power level exceeds approximately 10 hp, but this figure can vary significantly. An HLH's VHP flight-control hydraulic system could show as much as a 20 to 30% weight reduction. Typical Army helicopter flight-control system power levels are:

- Heavy Lift (YCH-62) - 70.0 hp.
- Medium Lift (CH-47C) - 24.5 hp.
- Utility (YUH-61A) - 12.3 hp.
- Attack (YAH-64A) - 8.8 hp.
- Observation (OH-58A) - 1.0 hp.

The utility hydraulic systems of some helicopters could also benefit from the use of 8000 psi systems. VHP technology shows the greatest weight benefits in power applications rather than those instances where servo-type controls are required. Engine starting systems fall into this category and are usually well above the 10 hp power level; for example, the CH-47C uses a 22 hp hydraulic system to start the T-55 turbine engine, and the YUH-61A uses an 18-hp pneumatic starter for the T-700 turbine engine that is also used on the YUH-60A, YAH-63A, and YAH-64A. This study showed a 27% weight decrease after VHP was applied to the 12-hp baseline hoist system. Ramp actuators are relatively large and heavy with extensive tubing and valve networks; weight advantages could be realized by applying VHP technology to this subsystem. APU start systems are also likely candidates. The baseline helicopter uses a 200 in.^{3} accumulator and a .95 CIPR motor to start the T-62 APU. A comparable VHP system would use a 75 in.^{3} accumulator and a .36-CIPR motor. The remaining APU start system valves and line weights would also be reduced.

The degree of applicability of VHP technology to a given aircraft hydraulic system is primarily a function of system size and power requirements of the vehicle. In large systems with relatively large lines and long runs, significant reductions in line and fluid weight can be realized. In smaller systems using small lines, line size reduction is limited by manufacturing and handling considerations, such as minimum practical line size and wall thickness, rather than flow velocity and pressure drop. Actuators in very large systems usually are big enough to permit a reduction in size when using VHP, resulting in significant weight savings. For low gross weight helicopters, which have smaller control loads and low control servo valve flows, there is no advantage to the use of VHP, because lower pressures are dictated by the output piston areas that will provide adequate flow and allow proper control valve manufacture. The potential for weight reduction in pumps and reservoirs varies with the degree of success of VHP application to system actuators and plumbing. A system large enough to permit significant reductions in actuator and line sizes will also permit significant reductions in pump and

reservoir weights. In a system where line sizes cannot be reduced because of manufacturing or installation restrictions, and actuators cannot be built smaller due to size or low flow control difficulties (resulting in subcircuits operating at less than 8000 psi), then reduction in pump and reservoir weights will be minimal.

The general industry consensus seems to be that future weight-reduction efforts will center on VHP systems with relatively conventional fluid distribution configurations (Reference 4). Therefore, it appears advantageous to concentrate Army development efforts in the area of actuator seal reliability, in order to be able to successfully apply VHP technology to helicopters once it has proved successful in high-performance fixed-wing aircraft. While VHP technology does not offer across-the-board improvements for Army helicopters, the advantages it does offer are substantial.

VHP SYSTEM DEVELOPMENT REQUIREMENTS

Introduction

VHP systems have been under successful development for 10 years. In certain areas, such as tubes and fittings, SOA technology will suffice. In other areas, significant development will be required.

Pumps

Eight hundred hours of testing on four units have shown no significant problems (Reference 44). But VHP pumps have yet to undergo the rigors of service usage for extended periods in severe operational and maintenance environments. Present pump technology does not allow an estimate as to exactly what problems, if any, can be expected. Rockwell has recommended a 750-hour VHP pump endurance test as part of the U. S. Navy Advanced Development Program.

Fluid

MIL-H-83282, which the latest U. S. Army helicopter programs specify, has been demonstrated as shear-table in VHP applications, and has excellent lubricity at 8000 psi (Reference 43).

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[44] Olsen, R. B., FOREIGN ACTUATOR TECHNOLOGY PROGRAM, Vought Systems Division of the LTV Aerospace Corp., Naval Air Development Center, Contract N62269-73-C-0262.

Additional testing is required to confirm its adequacy as a VHP fluid for long-term usage. At least a portion of this task could be accomplished during the 750-hour test mentioned above.

Servo Valves

No commercial electrohydraulic servo valves are currently available for use at 8000 psi. The Columbus Aircraft Division of Rockwell Corporation has developed a single-stage electrohydraulic valve for use in VHP systems (Reference 44). Conventional design and fabrication techniques were employed to make the valves; no state-of-the-art advances were required.

While single-stage valves are usually heavier and more bulky than two-stage valves, their use in VHP systems might be advantageous because of higher efficiencies due to lower first-stage losses. It is also possible that the single-stage concept could be developed to offer improved reliability for both VHP and conventional pressure applications.

Seals

This is a particularly critical area of VHP development relative to U. S. Army helicopters. Except for the effect of helicopter vibrations on hydraulic system components, actuator seal wear probably deserves the greatest attention (References 1 and 5).

Cyclic feedback loading (discussed in the SOA section of this report, with its wear-generating particles, imposes a more severe wear problem on helicopter flight-control actuators than fixed-wing aircraft actuators are likely to encounter. In addition, U. S. Army helicopters routinely operate in dust environments that most high performance fixed-wing aircraft never experience. In these situations, inadequate or worn scraper rings create an additional burden on the fluid seals.

To this point, 100 VHP test hours have accumulated on 22 different seals. Table 9 shows the results of these tests. The seals were tested at 8000 psi and +200°F. Dynamic seals were subjected to a total of 440×10^3 oscillations while static seals saw a total of 880×10^3 pressure pulsations. By comparison, in a 1200-FH period, each CH-47C rotor control actuator dynamic seal will be subjected to approximately 5×10^6 large-displacement cycles due to control inputs and 52×10^6 small-displacement cycles due to feedback loading.

Thus far, the U. S. Navy has funded approximately 1.7 million dollars for development of VHP technology. The Navy is currently planning to launch a 4-year full-scale Advanced Development Program for the application of VHP technology to fixed-wing aircraft. High cyclic rate feedback loading is not critical in fixed-wing aircraft and therefore will not be investigated. The anticipated 4-year plan makes no provision for this type of testing to be conducted.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

State-of-the-Art System Problems

There are three major generic problem areas in current Army helicopter hydraulic systems:

1. Plumbing Leaks
2. Fault Isolation Difficulties
3. Seal Life Reliability

Plumbing leaks and inadequate seal life have a negative impact on reliability, maintainability, safety, and LCC. Fault isolation difficulties result in the false removals of operable components, thereby degrading aircraft availability and maintainability, plus increasing LCC.

ACP System

The ACP system is representative of third generation systems about to enter the fleet on UTTAS, CH-47D, and the AAH. The ACP system promises reliability, maintainability, safety and survivability advantages over the baseline state-of-the-art system, but at higher cost and weight. ACP system benefits stem from the use of improved component technology and system layout concepts, plus early attention to design details. The improved technology was most evident in the use of new tube fitting designs and swaged connections. Improved layout concepts and design detail attention was evidenced primarily in the use of modularization, deactivation of flight control hydraulic systems during normal ground operations, deactivation of non-essential hydraulic systems during flight, and the inclusion of fault isolation aids.

The ACP system design can potentially reduce many of the generic problems associated with today's helicopters. Plumbing leaks can be sharply reduced through modularization and the use of advanced plumbing components. The use of modularization and simple fault isolation aids should reduce the fault isolation problem, however, the cost-effectiveness of additional sensors and modularization cannot be determined until a methodology to properly assess the penalties and benefits is developed. As hydraulic systems become more complex, this problem will require more attention. The impact of third generation hydraulic systems on the

problem of seal leakage is more difficult to define since the evolutionary seal designs now entering service have accumulated relatively little actual service, and on the UTTAS and AAH aircraft most information is competition-sensitive. Some reliability improvements are expected but these improvements are not believed to be on the order of a quantum increase in hydraulic system seal life.

Fault isolation difficulties are not related to system pressure levels, it affects both convention pressure and VHP systems. The section of this report that dealt with ACP system development requirements noted that a proper balance between diagnostics and system modularization was required to solve this problem.

VHP System

The VHP system evaluated in this report employed techniques similar to those used in the ACP system to obtain comparable reliability, maintainability and safety improvements over the baseline system. VHP technology provided further improvements over the ACP system in weight and survivability, plus reduced the size of system components. These further improvements were obtained with no increase in cost over the ACP system.

VHP technology offers more benefit to large fixed wing aircraft than to Army helicopters because most helicopters employ hydraulic systems of relatively low power. For this reason, the other military services are more logical major developers of VHP technology. However, VHP technology offers sufficient survivability and weight reducing benefits to warrant Army interest.

Unvented Cascaded Seals

The unvented cascaded seal concept is potentially capable of dramatically extending actuator seal life. The USAF is testing an unvented seal installation at Hill AFB in Utah. They have accumulated 250,000 cycles in a test that is planned to last for a minimum of 800,000 cycles. If unvented cascaded seal installations prove to be as reliable as expected, they would offer considerable LCC savings for all hydraulic pressure systems.

RECOMMENDATIONS

Fault Isolation

A means must be developed to weigh the summed costs of modularization and diagnostics against the penalties associated with inferior system fault isolation characteristics. These penalties include increased parts procurement and

stockage costs, decreased helicopter availability and mission reliability, as well as increased MMH costs. Presently, there is no means to readily weigh and compare the costs associated with these penalties.

A field investigation should be initiated to determine the relationship between component failure rates and incorrect removals. This relationship must be determined by on-site observation and testing since aircraft log books and data reporting systems are not geared to accurately present this information. The initial program stage should also be aimed at determining the full costs of incorrect removals. If the results of this first effort indicate that sufficient cost savings potential exists, the program should be extended to additional stages that will:

1. Determine the impact of system type and complexity on the removal rate, and quantify the influencing variables.

2. Develop a method of identifying system layouts and component installations that are susceptible to incorrect removals.

3. Identify the impact of highly modularized hydraulic systems when fleet system modifications are required.

4. Use knowledge gained in the earlier stages of the program to develop a means of determining the most cost effective mix of diagnostics and modularization. The method would have to require only a minimum of inputs in order to allow its frequent use during the design and development of a hydraulic system.

VHP System

Army VHP development efforts should be directed at monitoring U. S. Navy and USAF programs to identify those areas where separate or additional development efforts are required because of requirements that are peculiar to helicopters. A logical near-term Army VHP effort would be to concentrate on VHP seal development, particularly in the area of high cyclic rate seal wear. This latter task can be accomplished by fabricating the 8000 psi actuator described in Appendix A of this report (or a more simple seal testing device) and subjecting various seals to simulated helicopter operating conditions. The following tasks are recommended as logical next steps in a development program:

TASK I Design and Fabricate 8000-psi Actuator

1. Detail actuator components

2. Fabricate detail parts

3. Assemble actuator and functional-test

TASK II Conduct Endurance Test

1. Build test setup

2. Conduct simulated load cycling test

TASK III VHP Program Coordination

1. Monitor Navy programs for applicability of VHP technology to helicopters

Unvented Cascaded Seals

Although the USAF has initiated testing of an unvented seal installation, U. S. Army helicopter actuator seal requirements are diverse enough to warrant a separate development program that builds upon the USAF experience. The Army program should concentrate on the high cyclic rate, low excursion characteristics of helicopter rotor control actuators.

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LIST OF SYMBOLS

A	area
ACP	advanced conventional pressure
AFCAS	advanced flight control actuation system
AGB	accessory gearbox
APU	auxiliary power unit
BF	burst factor
Btu/min	British thermal units per minute
CAD	Columbus Aircraft Division
C_D	orifice discharge coefficient
CIPR	cubic inches per revolution
CP	collective pitch
CRES	corrosion resistant steel
d	inner diameter
D	outer diameter
DHS	dual-hardness steel
EDV	electrical depressurization valve
ESVA	equivalent singly vulnerable area
F	failure
°F	degrees Fahrenheit
FARADA	failure rate data
FH	flight-hour(s)
FMEA	failure mode and effect analysis
FSR	flight safety reliability
ft/min	feet per minute
gpm	gallons per minute

GSE	ground support equipment
HLH	heavy lift helicopter
hp	horsepower
Hz	Hertz-cycles per second
IAP	integrated actuator package
in.	inch(es)
$in.^2$	square inch(es)
$in.^3/sec$	cubic inches per second
kva	kilo voltamperes
lb	pound(s)
LCC	life-cycle cost
LVDT	linear variable displacement transformer
MAP	modular actuator package
MLH	medium lift helicopter
MMH	maintenance man-hours
MS	military standard
MSP	maintenance support positive
MTBF	mean time between failures
MTBR	mean time between removals
M/N	model number
NADC	Naval Air Development Center
nm	nautical miles
P	pressure
ΔP	differential pressure
P_L	load pressure
P_S	supply pressure

PSGE	peculiar ground support equipment
P/N	part number
psi	pounds per square inch
psig	pounds per square inch gage pressure
PTU	power transfer unit
QD	quick disconnect
Q_L	load flow
R	reliability
R&D	research & development
rpm	revolutions per minute
SAS	stability augmentation system
sec	second (time)
SOA	state of the art
VHP	very high pressure
ρ	mass density
β	bulk modulus
τ	time constant
ℓ	length
ω	radians/sec
λfs	reliability (flight safety)
δa	damping ratio

APPENDIX A

VHP ACTUATOR DESIGN AND ANALYSIS

INTRODUCTION

The Columbus Aircraft Division (CAD) of the Rockwell Corporation performed the following preliminary design and stability analysis of a VHP rotor control actuator for the baseline helicopter. Additional background information is contained in Reference 43, which documents the entire CAD program effort that was performed under subcontract to Boeing Vertol. The work in this appendix was performed in order to obtain a better perspective of the advantages and problems associated with designing a VHP actuator for helicopter rotor control. The design and analysis allowed the accomplishment of more accurate reliability, vulnerability, and weight evaluations, plus an assessment of VHP actuator stability. Conclusions related to this design and analysis can be found in the Evaluation and VHP Development Requirement sections of this report.

BASELINE ACTUATOR DESIGN FEATURES

There are two types of upper control actuators on the baseline CH-47C: swiveling and pivoting. They are identical in operation, but differ in loading and mounting. The two configurations are shown schematically in Figure A-1; design data are summarized in Table A-1.

Each actuator is a moving-body, dual-parallel unit controlled by a three-way spool/sleeve valve. A functional schematic of the actuator is presented in Figure A-2. Fluid is ported to and from the valve through the actuator piston/rod, eliminating the need for flexible supply lines. This unique design feature was used because of the 12.5 in. control stroke and 12-Hz feedback oscillations to which the actuator is subjected. The retract side of the piston is exposed to 3000 psi at all times; the three-way valve modulates pressure between 0 and 3000 psi on the extend side. Because of the piston area ratio, the actuator output force is zero when the modulated pressure is 1200 to 1250 psi.

VHP ACTUATOR DESIGN FEATURES

The conceptual 8000-psi actuator duplicates the 3000 psi upper control swiveling actuator both functionally and physically. Structural attach points, bearing sizes, and clearances are all retained. To meet current military specifications, the valve housing and actuator cylinders are rip-stop configured and made of steel. Although the swiveling actuator was designed, the concept is equally applicable to the

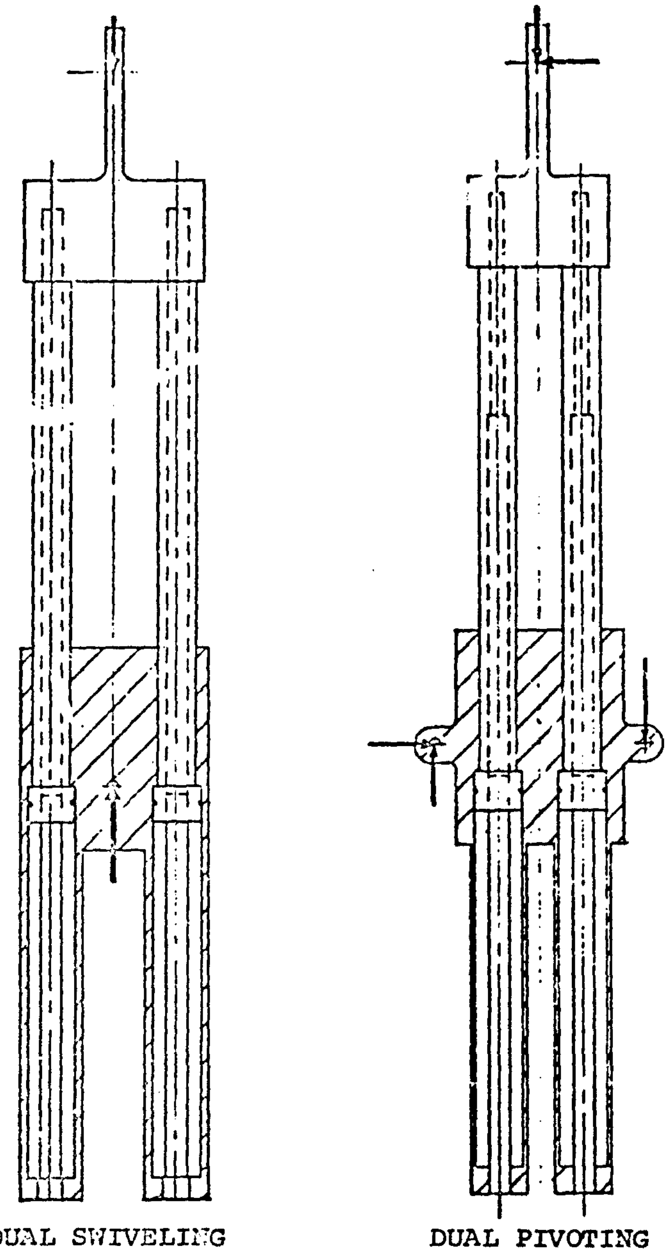


Figure A-1. CH-47C Upper Control Actuators.

TABLE A-1. VHP ACTUATOR DESIGN DATA

Operating Pressure	8000 psi
Stroke	12.5 in.
Rod Diameter	1.375 in.
Piston Diameter	1.678 in.
Quill Diameter	0.738 in.
Extend Side Area	0.4278 in.^{2}
Retract Side Area	0.7388 in.^{2}
Force Output (max)	
Extend	3422 lb
Retract	2424 lb
Actuator Flow (Rated)	
Extend	0.83 gpm
Retract	0.59 gpm
Cylinder Wall Thickness	0.125 in.
Design Loads	
Endurance Limit	±1800 lb (Dual sys)
Compression Limit	4682 lb/cyl
Tension Limit	3350 lb/cyl
Operating Loads	
Level Flight (max)	2000 ± 2200 lb
Typical High Speed Flight	2000 ± 1750 lb
Max Maneuver	6500 lb (Compression)

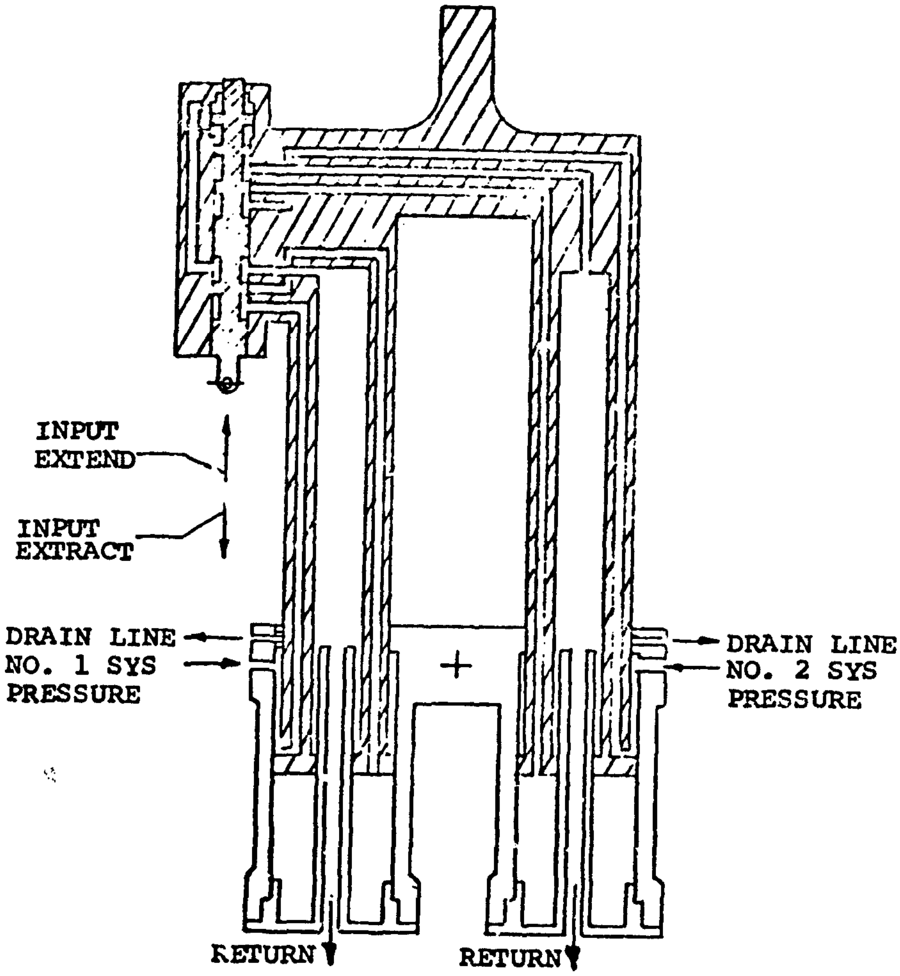


Figure A-2. Baseline CH-47C Upper Control Actuator Schematic.

pivoting actuator. The VHP swiveling actuator is shown schematically in Figure A-3; pertinent design data are listed in Table A-1. A conceptual layout drawing is presented as Figure A-4.

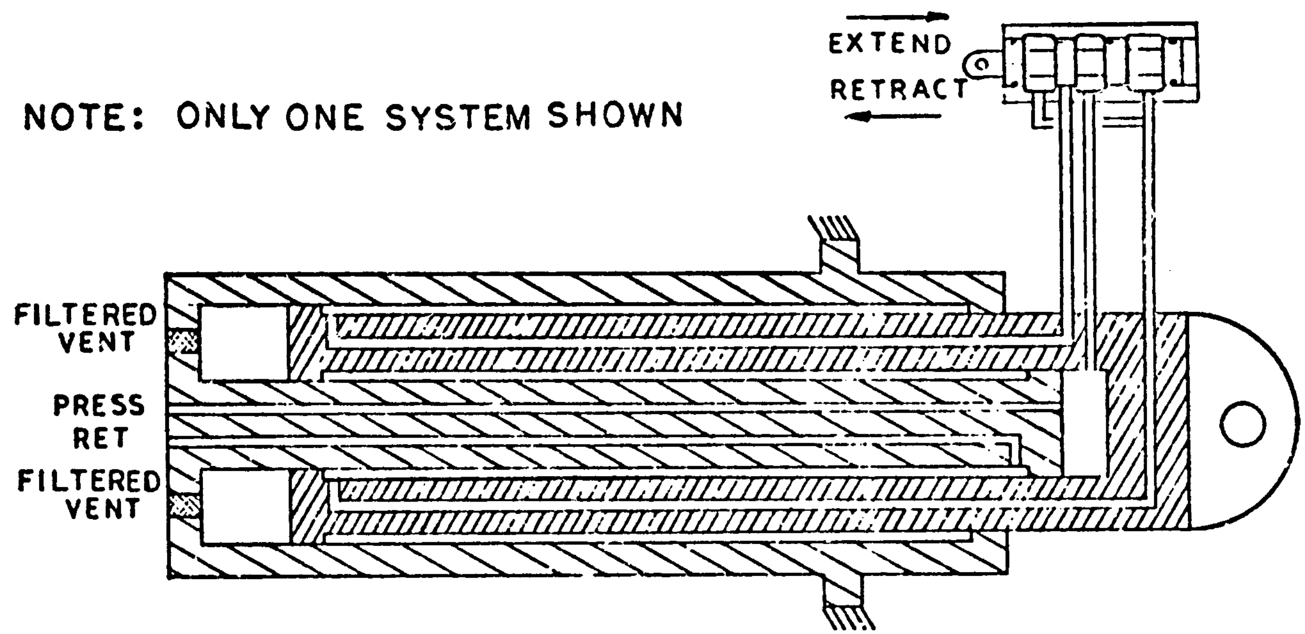
The piston extend area (piston area minus quill area on the baseline actuator) is relocated from the bottom to the top of the VHP actuator inside the rod (quill piston area). The quill contains pressure and return porting to supply fluid to both the extend area and three-way valve. The extend side of the quill piston is subjected to 8000 psi at all times; the three-way valve modulates pressure between 0 and 8000 psi on the retract side of the rod piston.

The VHP actuator output force is not exactly the same as the baseline, because this would have required special size piston and quill seals. In order to use off-the-shelf seals, the theoretical quill and piston diameters were changed to accommodate the nearest size standard seal. The baseline and VHP actuator outputs (two systems) are compared below:

	CH-47C	VHP	Increase
Max extend force, lb	6,264	6,844	9.3%
Max retract force, lb	4,510	4,848	7.5%

Although the baseline and VHP actuators are physically interchangeable, the VHP system differences are:

1. The pressure port is relocated to the lower end of the cylinder.
2. Cylinder centerline spacing is reduced from 4.5 to 4.0 inches.
3. The valve housing is in two sections for rip-stop design and is smaller in overall size.



SCHEMATIC

Figure A-3. 8000-PSI Upper Control Actuator.

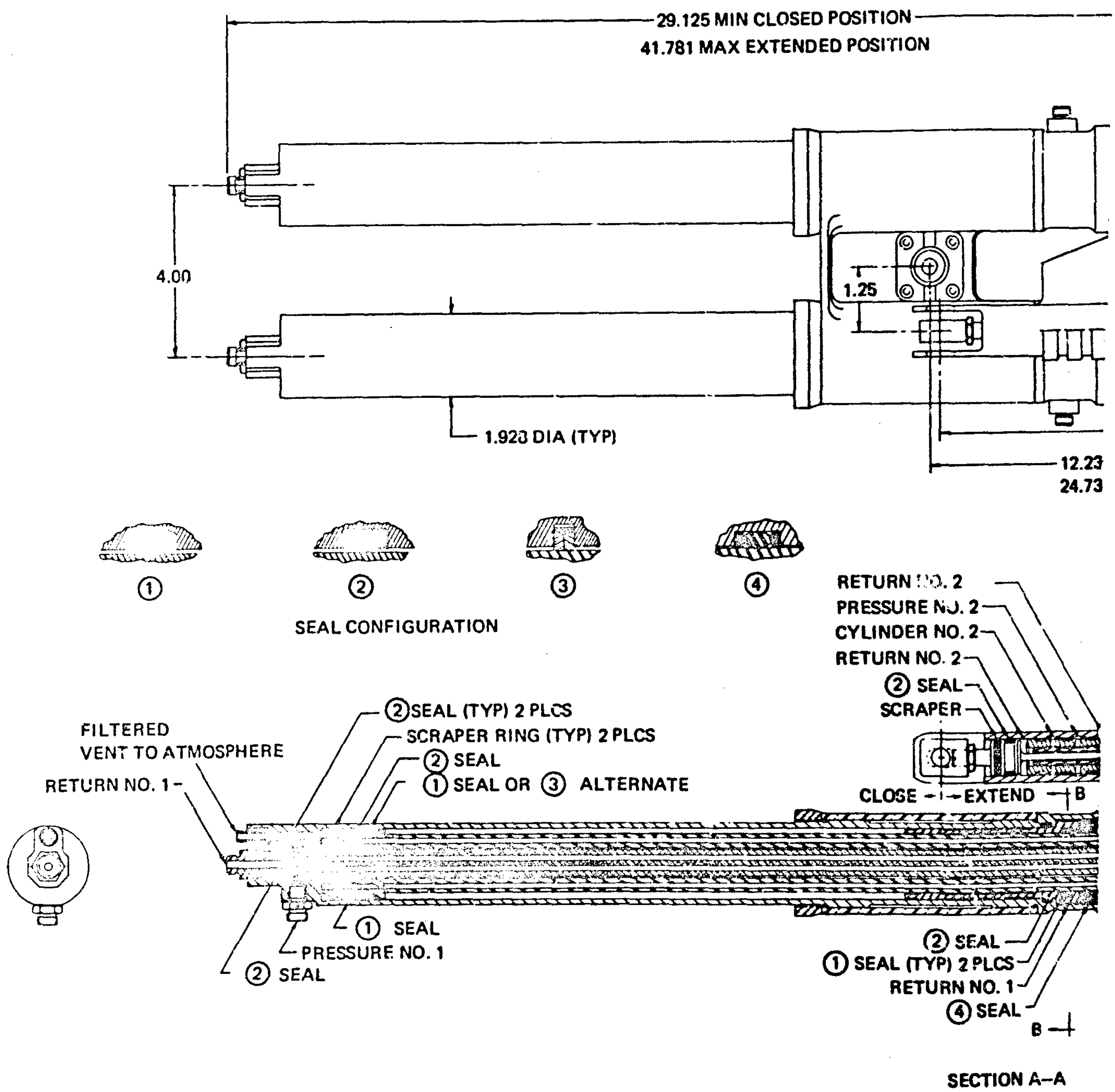
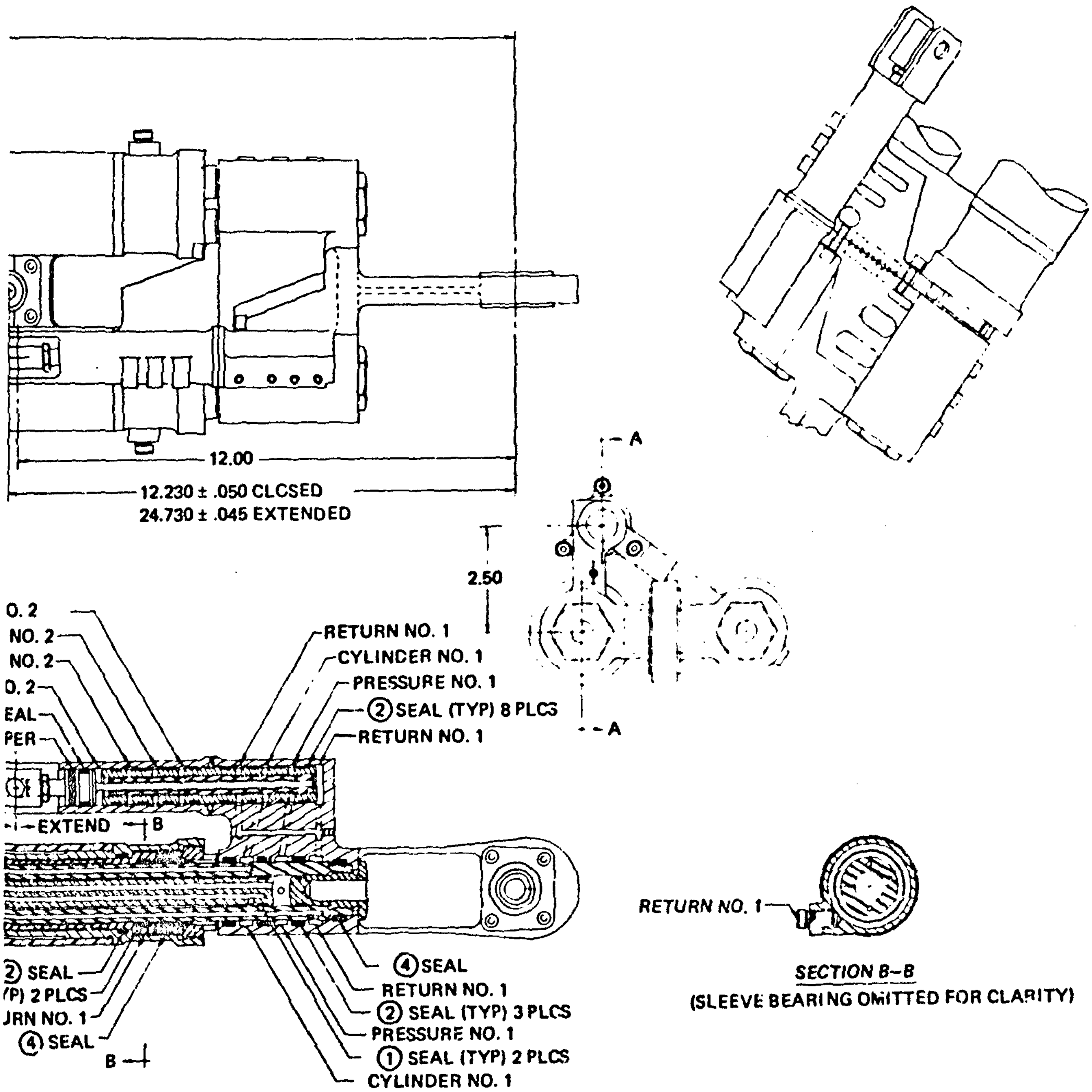


Figure A-4. 8000-PSI Upper Control Actuator Schematic.



SECTION A–A

SECTION B–B
(SLEEVE BEARING OMITTED FOR CLARITY)

(1)

Static stiffness of the baseline and VHP actuators is calculated later in this appendix. The effect of actuator stiffness on total system stiffness was estimated as follows:

Item	Baseline	VHP	% Change
Actuator, lb/in.	60,300	43,800	-27.4
Linkage, lb/in.	2,000	2,000	0
Backup Structure	40,000	40,000	0
Total System, lb/in.	1,846	1,825	-1.14

Linkage is the predominate factor affecting compliance. Although the difference between the two systems in resisting externally applied loads is negligible, the VHP actuator cylinder/piston interface will experience greater relative motion during 12-Hz oscillation loading.

COMPONENT DESIGN FEATURES

Cylinders

The actuator cylinders are made of PH13-8MO CRES steel, heat treated to 200,000 psi. This is a high-performance material which has been used extensively in the B-1 aircraft program and which has several important properties in addition to high strength:

1. Excellent resistance to stress-corrosion.

2. Excellent notch toughness.

3. Excellent machineability.

Use of PH13-8MO will minimize fabrication costs by eliminating plating and intermediate machining operations normally required for parts made from corrosion-sensitive low-alloy steels such as 4340.

Cylinder-wall thickness is sized to provide infinite life based on ±1800 lb (900 lb/system) endurance loading. Cylinder-bore diametral expansion due to system pressure is 0.00255 in.; this is well within the compliance capability of the recommended piston seals.

The closed end of each cylinder contains an air vent with a 5-micron replaceable filter to prevent entry of foreign material.

Piston/Rod

The piston/rod is fabricated from 4340 alloy steel, heat-treated to 180,000 psi, and has a ground chrome-plated surface. Two gun-drilled holes provide pressure and return porting for the actuator. Internal glands house a Turcon scraper ring and a T-seal to hold return pressure around the quill.

The piston has a two-stage seal and a Turcon scraper ring, (Figure A-5). A drain between the two stages is provided to port leakage past the first stage to return. This arrangement insures lubrication of the high pressure seal.

The piston seal is one of the most critical areas in the actuator because of the small 12-Hz oscillations which the piston experiences during normal flight. 21,600,000 oscillations occur in 500 flight-hours; this cyclic rate imposes severe demands on the piston seal and bore rubbing surface. As discussed in the VHP Development section, VHP seal endurance testing has been limited. However, two piston seals have shown excellent potential and are recommended by Rockwell as alternates for the VHP actuator. These will be described briefly.

One configuration, manufactured by Greene, Tweed is a standard T-seal with two-piece backup rings. Backups next to the T-seal are made from molybdenum disulfide loaded glass-filled Teflon. The outside backup is made of 316 CRES steel. The other recommended seal is manufactured by Cook Airtomic and consists of three separate steel rings. The two sealing rings are split and indexed to insure that the openings are 180° apart and that they prevent relative motion. The third ring, located in the groove bottom, acts as a spring to insure that the sealing rings contact the cylinder wall.

Whether either or both of the recommended piston seals would perform satisfactorily in the VHP actuator can only be determined by tests under simulated operating conditions. However, the following data are presented to support the recommendations:

1. The Greene, Tweed seal has been used successfully in helicopter rotor-control actuators and at 8000 psi (Reference 29).

2. The Cook Airtomic seal has been used successfully at 4000 psi in B-70 flight-control actuators (Reference 25) and at 8000 psi (Reference 29).

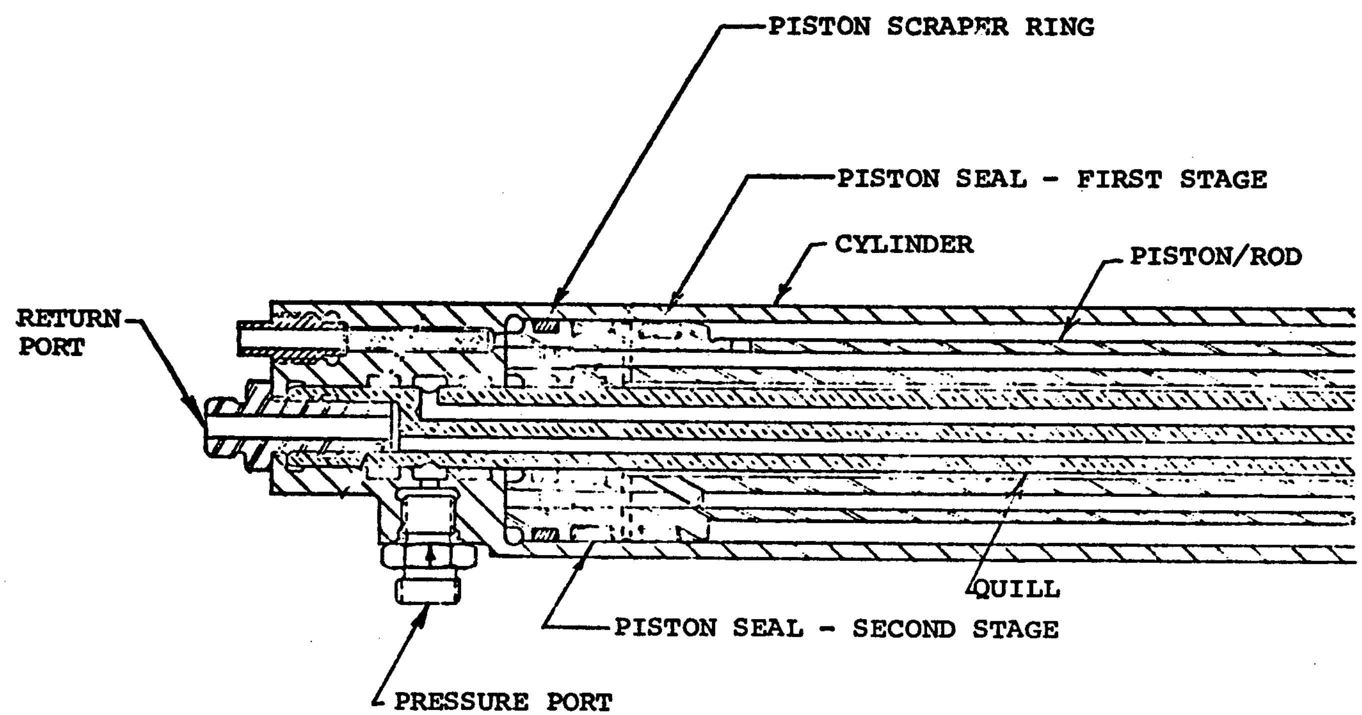


Figure A-5. Cross Section of VHP Actuator Piston.

Valve Housing

The valve housing is designed in two pieces and made of PH13-8MO CRES steel, heat-treated to 200,000 psi. The housing contains the spool/sleeve valve and porting from the valve to the cylinders, provides a structural tie for the dual cylinders, and contains the actuator rod end. The two parts of the housing are joined by four bolts near the flange on the valve sleeve. The design is such that crack propagation from one hydraulic system to the other is virtually impossible. Lightening holes were employed to minimize weight.

Spool/Sleeve Valve

The valve assembly is a dual tandem, three-way, proportional control unit (Figure A-6). Design data are given in Table A-2. The sleeve has a flange at mid-span to facilitate assembly, maintain concentricity between the valve and housing, and to lock the sleeve axially. An input rod passes through the spool and is furnace brazed to the spool end opposite the input. This arrangement permits only axial loads to be applied on the spool and eliminates binding. The rod is sized for a 255 lb shearout load. Valve adjustment is made at the input clevis. Diametral seals on the sleeve are "T" seals with two backups; the glands are standard size. A "T" seal with two backups and a scraper ring are used at the spool input.

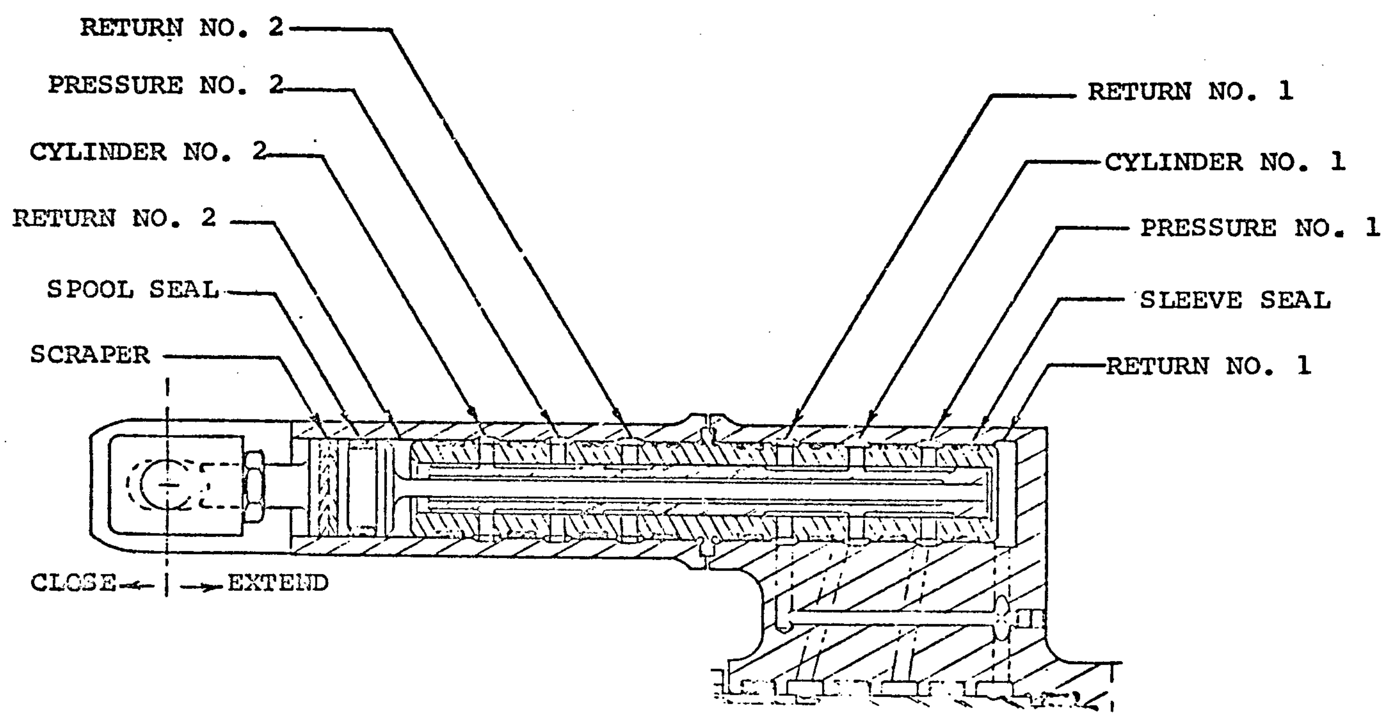


Figure A-6. Cross Section of Spool/Sleeve Valve.

TABLE A-2. VHP SPOOL/SLEEVE VALVE DESIGN DATA	
Actuator/Valve Gain (No Load)	60
Valve Flow Gain	43.85 $in.^3/sec.in.$
Valve Flow (Single System)	5.48 $in.^3/sec$ (1.42 gpm)
Valve Stroke	±0.125 in.
Flow Control Slot Width	0.008 in.
Dead Band	±0.003 in.
Input Lever Load Limit	255 lb
Sleeve O.D.	0.863 in.
Spool O.D./I.D.	0.438/0.200 in.
Spool Spindle Dia.	0.156 in.

STATIC STIFFNESS

Static stiffness of the VHP upper swiveling actuator can be represented by the model shown below:

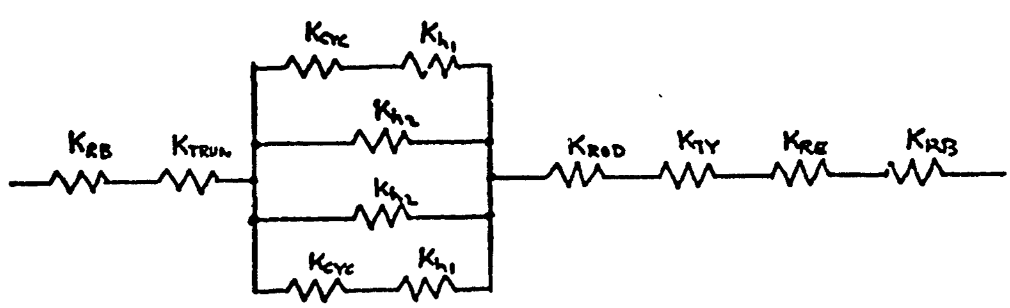


Table A-3 compares the static stiffness of the baseline actuator to the VHP actuator.

TABLE A-3. STATIC STIFFNESS

Element	Symbol	Baseline Actuator (lb/in.)	VHP Actuator (lb/in.)
Rod Bearing	K_{RB}	$.314 \times 10^6$	$.314 \times 10^6$
Cylinder Attachment	K_{TRUN}	162×10^6	383×10
Actuator Cylinder	K_{CYC}	$.985 \times 10^6$	$.607 \times 10^6$
Actuator Hydraulic Spring (Return)	K_{h1}	1.49×10^4	1.06×10^4
Actuator Hydraulic Spring (Head)	K_{h2}	4.32×10^4	2.18×10^4
Piston Rod	K_{ROD}	9.64×10^5	1.52×10^6
Parallel Actuator Tie Member	K_{TY}	144×10^6	144×10^6
Rod End	K_{RE}	3.44×10^6	3.44×10^6
Actuator (Total)	K_T	60,300	43,750

$\underline{K_{RB}}$

Extrapolation of Data

$$K_{RB} = \frac{2(3120)}{348750} \; 17.5 \times 10^6 \text{ lb/in.} = .314 \times 10^6 \text{ lb/in.}$$

$\underline{K_{TRUN}}$

$$K_{TRUN} = \frac{48EI}{(\ell_{TRUN})^3} = \frac{48(10.5 \times 10^6)\ (2.57)}{(1.[illegible])^3} = \underline{3.83 \times 10^8 \text{ lb/in.}}$$

$$I = \frac{bh^3}{12} = \frac{.6(3.72)^3}{12} = 2.57$$

K_{CYC}

$$K_{CYC} = \frac{AE}{(\ell_{CYC})^3} = \frac{3.42(30 \times 10^6)}{16.9} = \underline{.607 \times 10^6 \text{ lb/in.}}$$

$$A = \frac{\pi}{4} \quad (1.803)^2 - (1.678)^2 = .342$$

K_{h1}

Diametrical Expansion

$$\Delta d = .00265 \text{ at } 8000 \text{ psi}$$

$$\Delta V = \frac{17.7}{2} \left[\frac{\pi}{4} (1.678 + .00265)\ (.00265)\right] = .0309 \text{ in.}^3$$

$$B_{CYC} = \frac{3.16(8000)}{.0309} = 8.18 \times 10^5 \text{ psi}$$

$$B_e = \frac{2.38 \times 10^5 (8.18 \times 10^5)}{2.38 \times 10^5 + 8.18 \times 10^5} = 1.84 \times 10^5 \text{ psi}$$

$$K_{h1} = \frac{1.84 \times 10^5 (.4278)^2}{3.16} = 1.06 \times 10^4 \text{ lb/in.}$$

K_{h2}

$$\Delta V = \frac{17.7}{2} \left[\frac{\pi}{2} (1.678 + .00265)\ (.00265)\right] = .0309 \text{ in.}^3$$

$$B_{CYC} = \frac{4.9(8000)}{.0309} = 1.27 \times 10^6 \text{ psi/in.}$$

$$B_e = \frac{2.38 \times 10^5 (12.7 \times 10^5)}{(2.38 + 12.7) \times 10^5} = 2.0 \times 10^5 \text{ psi}$$

$$K_{h2} = \frac{2 \times 10^5 (.7308)^2}{4.9} = 2.18 \times 10^4 \text{ lb/in.}$$

K_{ROD}

$$K_{ROD} = \frac{AE}{\ell} = \frac{1.09(30 \times 10^6)}{21.5} = 1.52 \times 10^6 \text{ lb/in.}$$

$$A = \frac{\pi}{4} \left[(1.373)^2 - (.704)^2\right] = 1.09 \text{ in}^2$$

$\underline{K_{TY}}$

$$K_{TY} = \frac{48EI}{\ell^3} = \frac{48(10.5 \times 10^6)\ (4.47)}{(2.5)^3} = \underline{144 \times 10^6 \text{ lb/in.}}$$

$$I = \frac{bh^3}{12} = \frac{(1.25)\ (3.5)^3}{12} = 4.467 \text{ in.}^4$$

$\underline{K_{RE}}$

$$K_{RE} = \frac{AE}{\ell} = \frac{(2 \times .6)\ (10.5 \times 10^6)}{3.66} = \underline{3.44 \times 10^6 \text{ lb/in.}}$$

$\underline{K_{TOTAL}}$

$$\frac{1}{K_{TOTAL}} = \frac{1}{K_{RB}} + \frac{1}{K_{TRUN}} + \frac{1}{\left(2\,K_{hz} + \frac{K_{CYC}K_{hi}}{K_{CYC}+K_{hi}}\right)} + \frac{1}{K_{ROD}} + \frac{1}{K_{TY}}$$

$$+ \frac{1}{K_{RE}} + \frac{1}{K_{RB}}$$

$$= 7.32\varepsilon \times 10^{-6} + \frac{1}{(2\ 2.18 \times 10^4 + 1.04 \times 10^4)}$$

$$K_{TOTAL} = 4.375 \times 10^4 \qquad \underline{43{,}750 \text{ lb/in.}}$$

DYNAMIC STIFFNESS

The dual-swiveling actuator was assumed to consist of two identical actuator systems driving a common load. System dynamics can then be described by one actuator driving one-half the load. A linearized simplified model of the actuator is shown on Figure A-7. The model was based on the following additional assumptions:

1. Viscous friction between the piston and cylinder was negligible and coulomb friction was zero.

2. Actuator piston/valve housing mass is much less than the effective rotor mass.

3. Spring rates of the piston rod, cylinder, oil column, etc., can be combined and described as an effective spring rate (K_h).

4. Check valve performance was assumed to be ideal.

The equations represented by Figure A-7 are summarized below:

$$\begin{bmatrix} -K_Q & +As & +\left(\frac{h^2}{K_h}s + K_{cz}\right) \\ 0 & (Ms^2 + Bs + K) & -A \\ 1 & K_{FB} & 0 \end{bmatrix} \begin{bmatrix} X_v \\ X_p \\ p \end{bmatrix} = \begin{bmatrix} 0 \\ -F_L \\ K_{in}\, X_{in} \end{bmatrix}$$

where,

K_Q	=	Valve flow gain
A	=	Actuator piston area
K_h	=	Actuator mechanical stiffness
K_{cz}	=	Valve flow-pressure coefficient (effective)
M	=	Load mass (piston, valve housing, etc.)
p	=	ΔP across piston
B	=	Load damping
K	=	Load spring
K_{FB}	=	Feedback gain
X_v	=	Valve SP position
X_p	=	Actuator piston position
F_L	=	External force applied to piston
K_{in}	=	Input gain
X_{in}	=	Input command

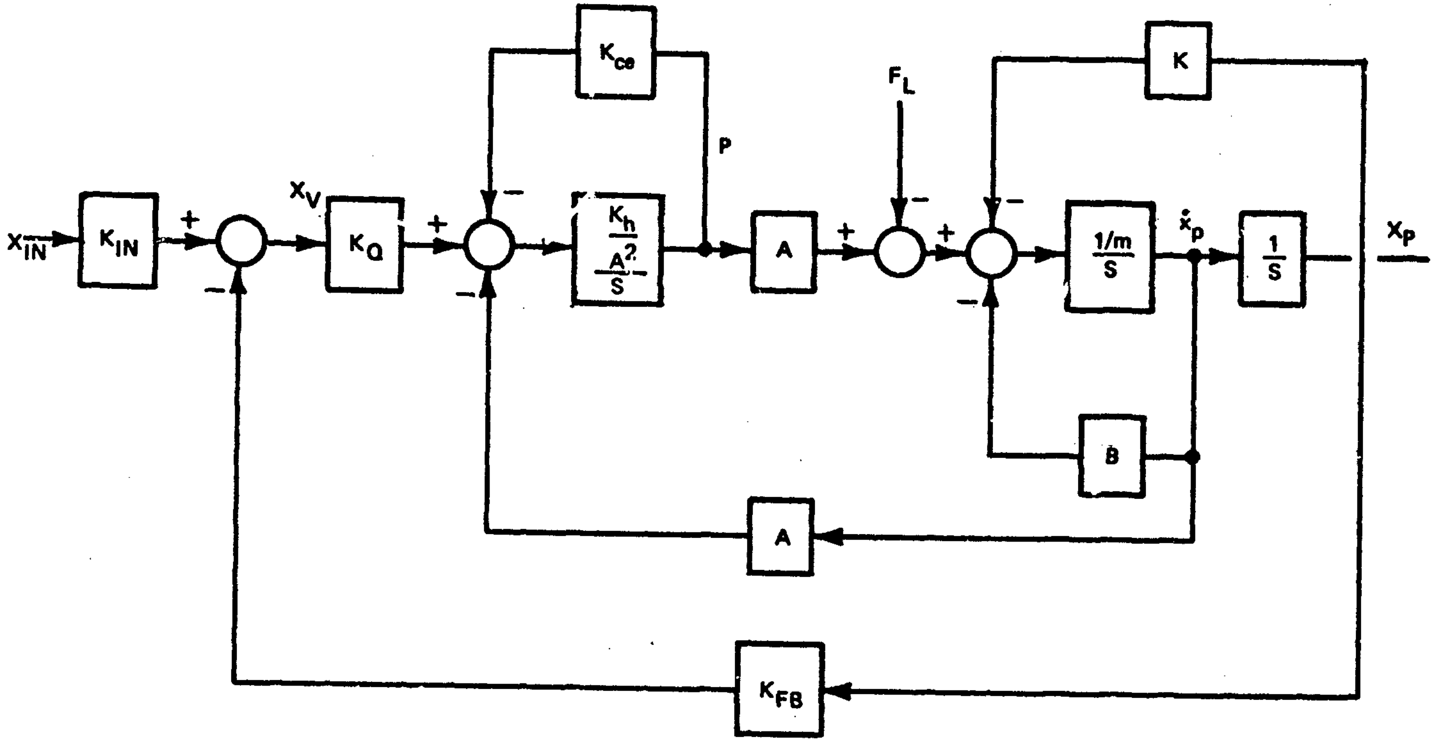


Figure A-7. Actuator Model.

Actuator stiffness (the inverse of compliance) is given by the transfer function:

$$\frac{F_L(S)}{X_p(S)} = \frac{\left(\frac{A^2M}{K_h}\right)S^3 + \left(\frac{A^2B}{K_h} + MK_{CE}\right)S^2 + \left(\frac{A^2K}{K_h} + BK_{CE} + A^2\right)S}{K_{CE}\ \frac{A^2}{K_hK_{CE}}\ S + 1}$$

$$+\frac{\left(K_{CE}K + K_QK_{FB}A\right)}{\left(K_{CE}\ \frac{A^2}{K_hK_{CE}}\ S + 1\right)}$$

This is of the form:

$$\frac{F_L(S)}{X_p(S)} = \frac{K_S\left(\frac{S^2}{W^2} + \frac{2\delta}{W}\ S + 1\right)\left(T_1S + 1\right)}{\left(T_2S + 1\right)}$$

Assuming K = D and load damping (B) is negligible compared to other damping terms, algebraic expressions for the factored transfer function are:

$$W \approx W_a = \sqrt{\frac{K_h}{M}}$$

$$\delta \approx \delta_a = \sqrt{\frac{K_{CE}}{2A^2}}\ K_hM$$

$$\tau_1 \approx \frac{A}{K_QK_{FB}}$$

$$\tau_2 \approx \frac{A^2}{K_hK_{CE}}$$

$$K_S \approx \frac{K_QK_{FB}A}{K_{CE}}$$

Calculated values for the 3000- and 8000-psi system coefficients and the above dynamic terms are presented in Table A-4. Since the piston/valve housing mass is small and the mechanical stiffness is large, the characteristic actuator frequency is high ($140H_z$)--far beyond the frequency of interest ($12H_z$). The stiffness transfer function therefore reduces to:

$$\frac{F_L(S)}{X_p(S)} = \frac{K_S\ \tau_1S + 1}{\tau_2S + 1}$$

The asymptotic value of this function as S increases is:

$$\frac{K_S \tau_1}{\tau_2} \approx \left(\frac{K_Q K_{FB} A}{K_{CE}}\right)\left(\frac{A}{K_Q K_{FB}}\right)\left(\frac{K_h K_{CE}}{A^2}\right) \approx K_h$$

Dynamic stiffness of the baseline and VHP actuators is shown on Figure A-8. The static stiffness (W = 0) is K_S which reduces to:

$$K_S \approx \frac{K_Q A}{K_{CE}} \approx K_p A$$

Total actuator stiffness values are summarized below:

	Baseline Actuator	VHP Actuator
Mechanical Stiffness	60,300 lb/in.	43,800 lb/in.
Static Stiffness at W = 0	3.72×10^6 lb/in.	3.1×10^6 lb/in.
Dynamic Stiffness at 12Hz	76,900 lb/in.	56,400 lb/in.

Based on the oscillatory load encountered during level flight ($\pm$2200 lb at $12H_z$), the dynamic stiffness values given above result in piston oscillations of $\pm$0.029 in. in the baseline actuator and $\pm$0.039 in. in the VHP actuator. Actual oscillations should be less than these estimated values because of assumptions used in the analysis. The two most difficult coefficients to predict were damping and valve flow-pressure characteristics around null. Damping affects the resonant peak and thus the loop gain limit. The flow-pressure coefficient is important because of its affect on damping and τ_2. The same loop gain was assumed for both the 3000- and 8000-psi configurations. Generally, however, 8000-psi systems inherently possess more damping than 3000-psi systems.

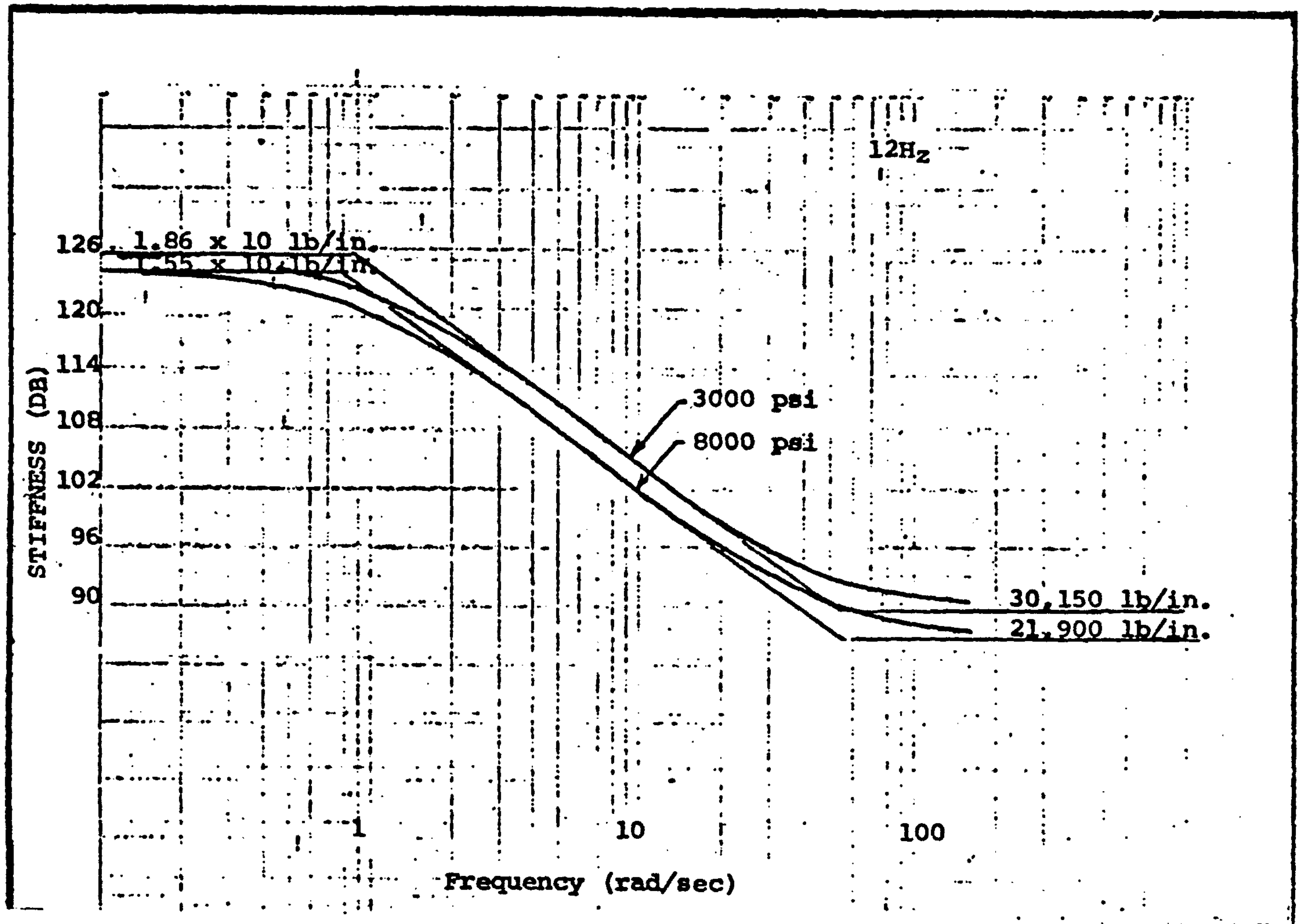


Figure A-8. Dynamic Stiffness.

Hydraulic actuators are non-linear devices, and as such, their dynamic characteristics vary with input signal level. At signals above the perturbation level assumed in the linearized analysis, damping increases rapidly.

CH-47 rotor control actuators experience ±0.025 in. oscillations when newly installed. The analysis presented herein is in good agreement with this value.

TABLE A-4. DYNAMIC STIFFNESS PARAMETERS

Parameter	3000-psi sys	8000-psi sys
A, in.^{2}	1.8432	.7808
M, lb-sec^2/in.	.031	.030
K_h, lb/in.	30,150	21,900
ω, rad/sec.	986	854
δ_a	.0020	.0022
K_q, in.^{2}/sec/in.	99.67	40.56
*K_p, psi/in.	1.01×10^6	2.12×10^6
$K_{CE} \approx \frac{K_Q}{K_P}$	$.985 \times 10^{-4}$	$.191 \times 10^{-4}$
K_v $\frac{K_a}{K_p}$	54.07	55.5
T_1 $\frac{1}{K_v}$	.0185	.0180
T_2	1.14	1.28
Static Gain $\approx K_s$ $\frac{K_v A^2}{K_{CE}} \approx K_p A K_{FB}$	18.6×10^5 (125.4 db)	15.5×10^5 (123.8 db)

*All data is for MIL-H-83282 fluid at +150°F.

APPENDIX B

SELECTION OF ADVANCED CONVENTIONAL PRESSURE HYDRAULIC SYSTEM

INTRODUCTION

Four hydraulic system concepts were considered. One concept, the cored transmission, was very advanced and would require extensive development work. Another concept, IAP, was somewhat less advanced, but would still require considerable development. The remaining two concepts were fully achievable within the latest state of the art. The four concepts were:

1. Cored transmissions, having two sets of actuator pumps, control components, reservoirs, and cooling systems as "plug-in" units, with fluid routing accomplished by tubes cast into the walls of the transmissions.

2. IAP, with each dual actuator package having integral pumps, reservoirs, control components, and cooling systems.

3. Modularized CH-47C type two-pump system, with PTU providing partial third system backup, and allowing ground operation of both flight-control systems for maintenance purposes. This is basically the system Boeing Vertol has proposed for the CH-47 modernization program but with some basic changes in the area of modularization and PTU capability.

4. Four completely independent modularized systems, two each fore and aft, with no hydraulic lines passing through the middle of the helicopter.

The four concepts reflect a wide variance of configurations. It was felt that proper concept selection was an extremely important factor in developing a 3000-psi ACP system to both improve the CH-47C, and compete with the VHP system. The concepts were defined by drawings and cutaway/sketches, plus oral and written descriptions. These are included later in this section. The objective was to provide the minimum amount of definition necessary for the reliability, maintainability, safety, survivability, weight and cost groups to make reasonable assessments. The definitions included discussions of concept variations, but in each instance, the final evaluation was of the basic system that was described. CH-47C configuration constraints were generally observed. A ground rule was established that only minor airframe sheetmetal modifications were allowed, but items such as new transmission or an extra pump drive pad on an existing transmission were considered acceptable.

The following decisions were made in order to simplify the evaluations:

1. The lower boost system was eliminated from the study.

2. Anti-jam provisions were not included in the conceptual definitions.

The CH-47C rotor-control configuration made a lower boost system necessary regardless of which hydraulic system concept was selected. All study concepts except the IAP provided hydraulic power in the area of the lower controls compartment. If the IAP were selected or in final contention, the impact of the additional dual power supply for the lower controls would have to be considered.

Anti-jam provisions were not provided in the rotor-control actuators because all four concepts would have employed nearly the same methods to obtain anti-jam capability. Including the feature would merely have complicated the study

Before the four concepts were fully investigated and defined, it appeared evident that the cored transmission system would greatly increase the CH-47C transmission envelope and would therefore rule the system out as an ACP candidate. A decision was made to keep the cored transmission concept in the study but devote less time to it. This was done in order to become familiar with the concept so as to later more effectively assess VHP benefits and shortcomings in this type of application.

The concept selected was the two-pump modularized system. A change from the original concept was made in that the PTU's no longer provide full third-system flight-control hydraulic backup. The PTU's do provide the capability of operating both flight-control systems for maintenance purposes without turning the rotor system, and could provide limited third-system control. The third-system full backup was deleted because:

1. Routing PTU-provided hydraulic power into the control module would have provided effective backup only in the case of a primary system pump failure and not when the primary system was disabled because of leakage. The major cause of primary system loss has been system leaks rather than pump malfunctions.

2. Routing PTU-provided power directly to each of the four dual rotor-control actuators and four lower boost actuators would have provided more effective backup, but would have required a complex electrical and hydraulic switching arrangement plus much additional tubing. Severe penalties in weight, cost, reliability and maintainability would have resulted.

The ACP concept selection process is delineated on the following pages. Documentation is in the sequence shown below:

- IAP system description
- Cored transmission system description
- Two-pump modularized system description
- Four-pump modularized system description
- Evaluation summary sheet
- Reliability evaluation
- Maintainability evaluation
- Safety evaluation
- Survivability evaluation
- Weight evaluation
- Cost evaluation
- Selected ACP flight-control hydraulic system
- ACP rescue hoist hydraulic system

Appendix C contains descriptions of component concepts that were also evaluated. These component concepts were not included in the basic ACP design because:

1. Selecting some concepts for inclusion in the ACP design and others for the VHP design would have resulted in confusion as to the benefits and drawbacks of each type component. Additionally, the impact of this confused situation on the ACP/VHP comparison issue would have further clouded that issue and made it difficult to extract the real benefits and shortcomings of either system.

2. The benefits and shortcomings of some component concepts were difficult to quantify, and therefore had to be addressed in general terms.

INTEGRATED ACTUATOR PACKAGES (IAP)

This concept would consist of five integrated actuator packages. Four dual IAP would replace the four CH-47C dual rotor-control actuators and their two hydraulic power systems. The fifth dual IAP would replace the present three dual SAS actuators and four dual lower stick-boost actuators, plus their assorted lines, filters, and control valves.

A dual rotor-control IAP is shown in Figure B-1. The hydraulic actuation cylinders are similar to those used on the CH-47C, with one completely independent hydraulic power-generating system attached to each of the dual cylinders. The cylinders and associated power supplies are joined structurally, but complete hydraulic separation is maintained. Figure B-2 provides estimated IAP envelope dimensions.

The independent hydraulic power-generation systems can be separated from the cylinder bodies. Integral self-closing valves could be used to reduce the possibility of particle and air contamination, and to decrease maintenance replacement time. The power-generating module would contain the following components:

- Reservoir
- Return filter
- Air separator
- Variable displacement pump, approximately 3 gpm at 3000 psi
- Electric motor, approximately 6.5-hp
- High-pressure filter
- Relief valve and miscellaneous check valves
- Pressure transmitter
- Accumulator with gas charge gage and charging valve
- Pressure switch
- Oil cooler
- Fluid-level transmitter (probably an LVDT)

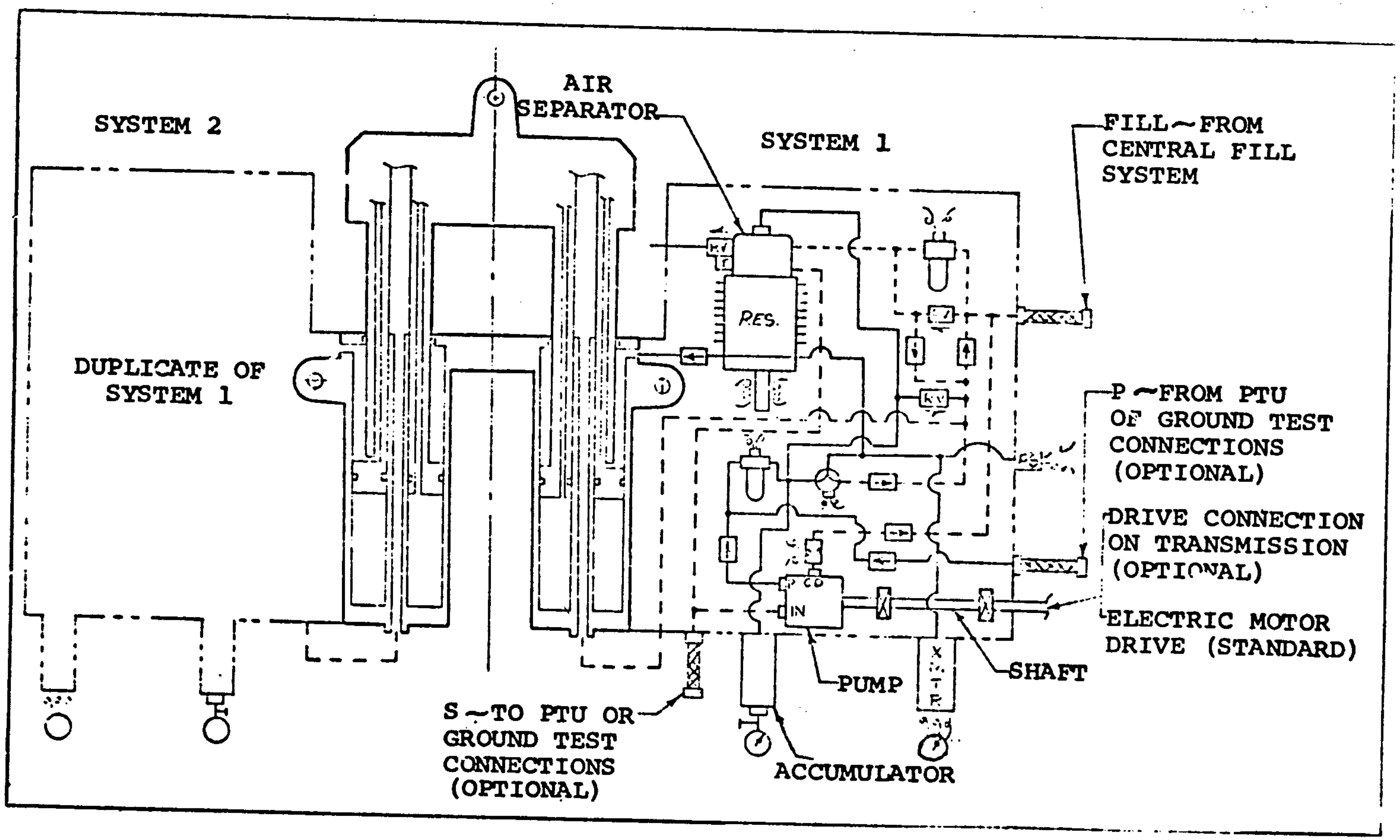


Figure B-1. Integrated Actuator Package Schematic.

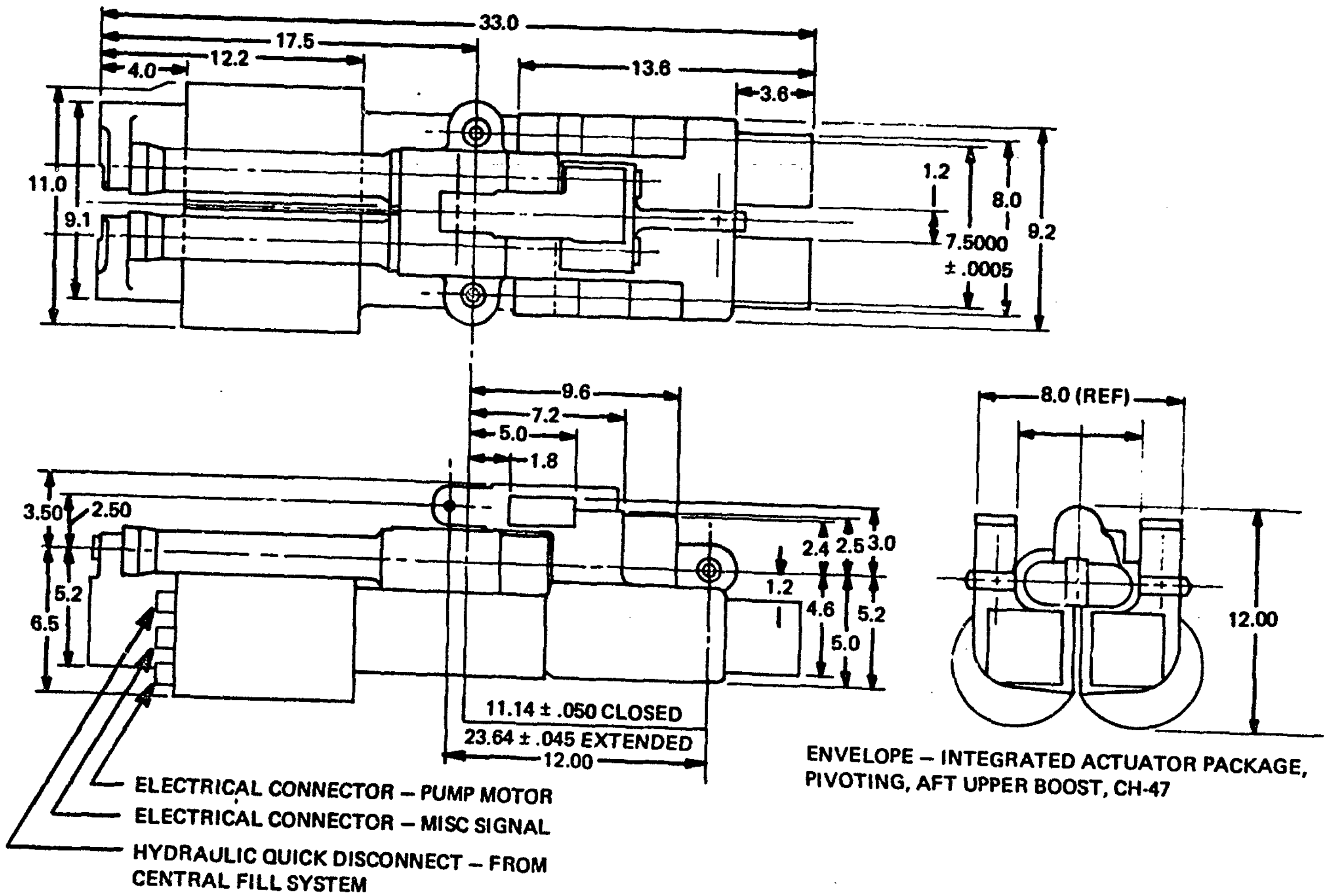


Figure B-2. Integrated Actuator Package Dimensions.

- Quick-disconnect (QD) hydraulic coupling half for central fluid servicing system

- Two electrical connectors; one connector provides power for the electric motor and the other for control and indicating signals.

- QD hydraulic coupling half for ground operations using a hydraulic power cart. (This could be omitted since full hydraulic power would be available using APU-driven aircraft generators or electrical ground power carts to provide power for the hydraulic pumps.)

There are a number of configuration options available. The electric motor could be deleted and drive power obtained from the rotor transmission. Power would be transferred via a flexible shaft or a double universal-jointed shaft connected to a drive pad on the transmission. However, actuator articulation during normal operation would make this a relatively complicated arrangement and reliability might be extremely poor.

Another alternative would be to mount two pump/cooler units on each transmission and route hoses to the actuator/control packages. This approach does not make maximum use of integration and introduces more leak points, but it would be less costly, lighter in weight, and easier to develop. It will be investigated further if the IAP concept scores relatively high in the concept evaluation phase.

Although the four dual IAP have identical systems and are made up of exactly the same components, the four units are not interchangeable. The two pivoting actuators have a different mount system than the two swiveling actuators. In addition, the forward actuators (one swiveling and one pivoting) must have the upper housing arranged and installed differently due to the space available at the transmission/structure/swashplate interface. For these reasons, four separate dual IAP would have to be stocked in supply. The expected high LCC therefore dictated having the power-generation modules separate, as was described earlier. New model helicopters could have differently designed transmissions, swashplates and mechanical controls inputs to accomodate one or two instead of four actuator configurations.

The lower stick-boost dual IAP would consist of two independent hydraulic power-generating systems connected to a structurally mounted manifold on which four dual integrated actuators are mounted. The integrated actuators would be in the pitch, roll, yaw, and collective pitch (C.P.) axis. All axes, except C. P.,

would have lower boost and SAS functions combined. The C. P. axis would have only the lower boost function. The integrated actuators would be similar to the units planned for the CH-47D Program.

The four integrated actuators are individually mounted to the manifold in such a fashion as to facilitate quick removals. Self-closing valves would be located on the manifold to permit actuator removal without system drainage or contaminant ingress.

The IAP would be located in the controls closet between Station 95 and Station 120, on the left-hand side of the cockpit entrance-way. The pitch and roll actuators would mount on the rear face of the manifold, while the yaw and collective actuators would mount on the forward face. The two independent power-generation units would mount on the inboard side of the manifold, which would contain self-closing valves so that the independent units could be quickly removable for maintenance purposes. In an actual CH-47C retrofit effort, it would not be possible to mount the power-generation modules inboard of the manifolds. The units would project 6 or 7 in. into the cockpit entrance-way, restricting it to 19 or 20 in. of width. The modules would have to be mounted on the compartment wall with hoses or tubes connecting them to the manifold. It is assumed that, for a new aircraft design, sufficient space could be provided for the IAP. Its approximate dimensions would be: 20 in. high, 12 in. wide, and 6 in. deep.

The power-generation modules would contain all of the elements listed for the rotor-control IAP, but pressure and flow requirements would be lower. Each variable displacement pump would deliver approximately 2 gpm at 1500 psi, while the electric motors would each be rated at 2.5 hp. Reservoir capacity would be approximately 25 in.^{3}. Because of man-hour constraints, a thermal study was not accomplished. However, cooling probably would be required, and it could range from having finned components to a cored cooler having an electrically-driven fan. The addition of a cooler/fan would increase the 20x12x6-in. dimension provided earlier by approximately 36 in.^{3}.

CORED TRANSMISSION CONCEPT

In this concept, each rotor transmission (forward and aft) contains dual integral hydraulic systems. To the extent possible, all fluid-distribution lines are contained within the walls of the transmission.

The most practical technique would be to fabricate the 3000-psi fluid-distribution lines into brazed (silver or copper) assemblies and then to cast the assemblies into a magnesium or aluminum housing. Components could bolt onto the transmission

housing wall as in Figure B-3, or be inserted into wall cavities as in Figure B-4. Low-pressure return lines could be drilled or cored into magnesium or aluminum alloy housings, or brazed lines could be employed. Some modern casting alloys may allow drilled or cored passageways for high-pressure fluid, but much additional development work would be required in this area.

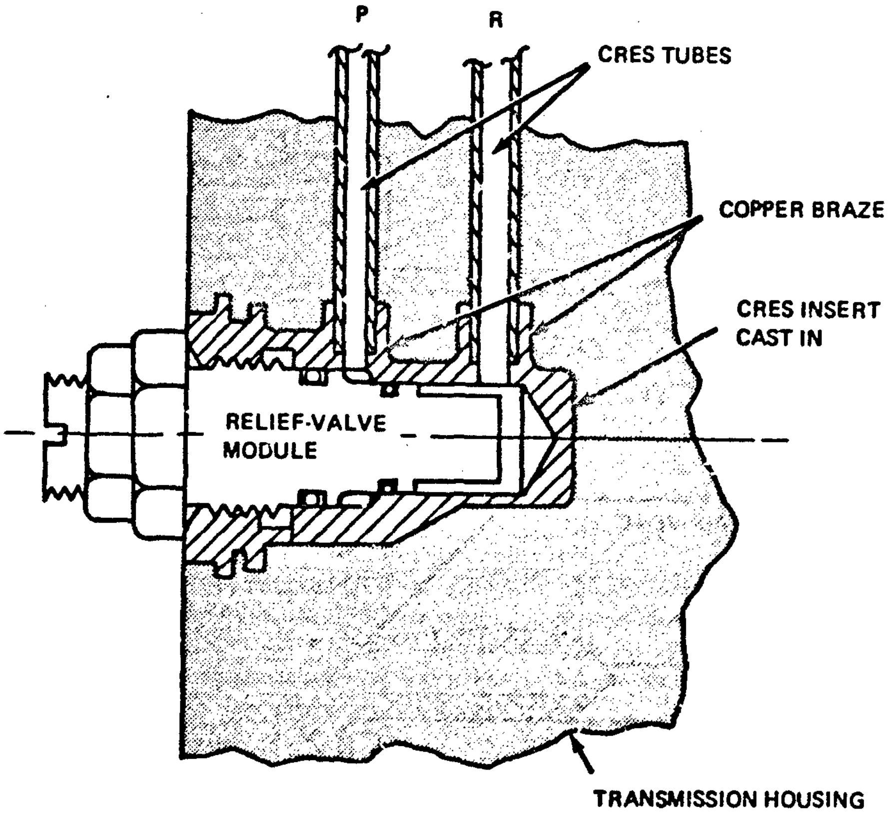
The rotor-control actuators would be integrated into the transmission housing cover which would have to be made of steel in order to react actuator loads. The present CH-47C rotor transmission covers are also made of steel, since axial, radial, and torque loads are taken into the transmission/air-frame mounts through the cover. Figure B-5 shows the proposed actuator installation. Note the clearance required around the actuator rod. Clearance is necessary because the rod will cock as misalignment occurs between the actuator (bottom rod connection) and the swashplate (top rod connection) as the stationary swashplate tilts. This necessitates an increase in the diameter of the actuator as compared to present CH-47C rotor control actuators.

This misalignment dictates a yoke-type connection at each end of the actuator rod, so it will be necessary to provide a special scissors assembly or similar device to allow vertical movement and tilting of the stationary swashplate, yet prevent it from rotating out of position relative to the actuators.

It is possible to devise various system arrangements having some components integral to the transmission and others external. The full benefits of this concept would probably be realized with all components, or all components except the actuators, integral to the transmission. It may not be practical to mount all components inside (or on the outside walls of) the transmission, since the increased transmission space requirement could be prohibitive.

TWO-PUMP MODULARIZED FLIGHT CONTROL SYSTEM

The two-pump modularized flight-control system was selected as the ACP system. Rather than include both a preliminary and a detailed description of the same system in this report, the preliminary description has been deleted. Refer to the Systems Description section for a description of the two-pump modularized flight-control system.



RELIEF-VALVE MOUNTING, TRANSMISSION

Figure B-3. Example of Hydraulic Valve Installed in Cored Transmission.

PUMP-FACE MOUNTING, INTEGRAL PASSAGES

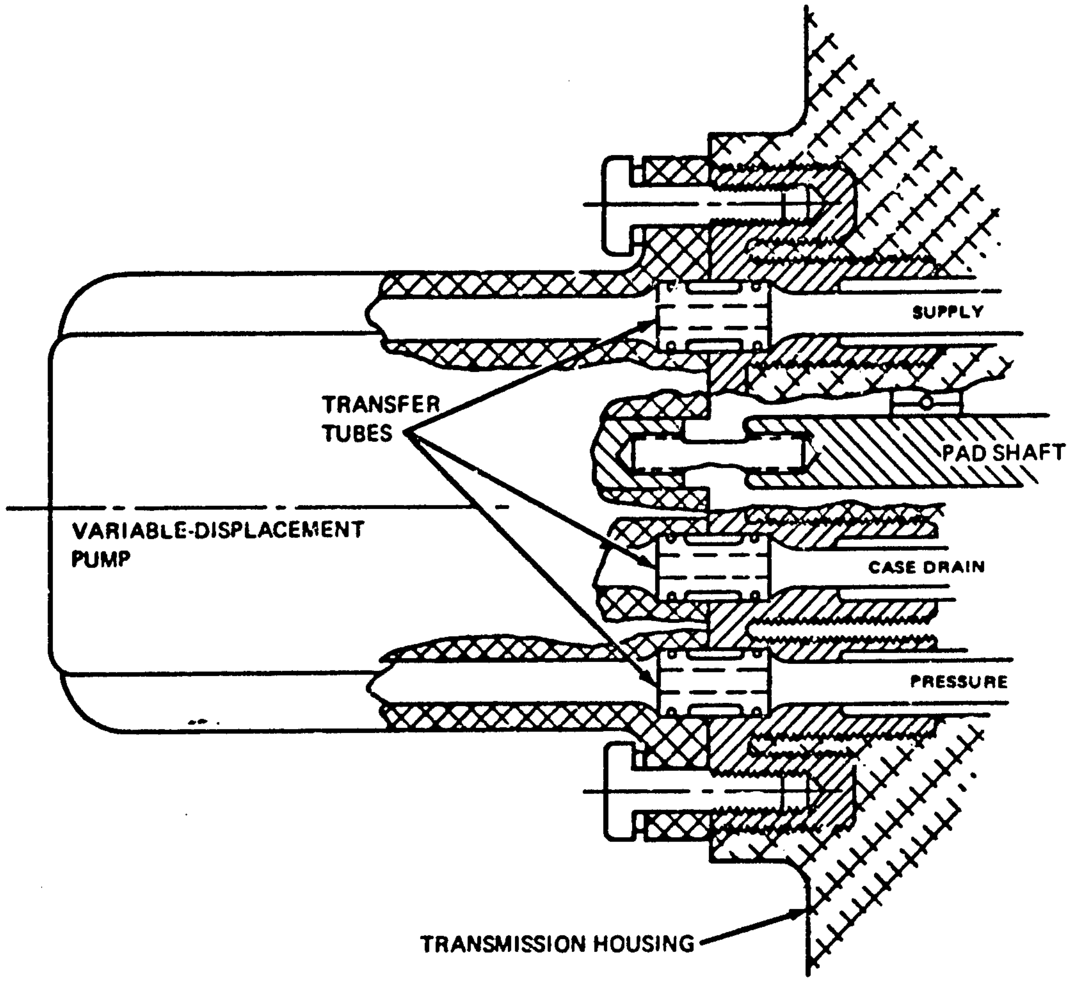


Figure B-4. Example of Hydraulic Pump Mounted on Cored Transmission.

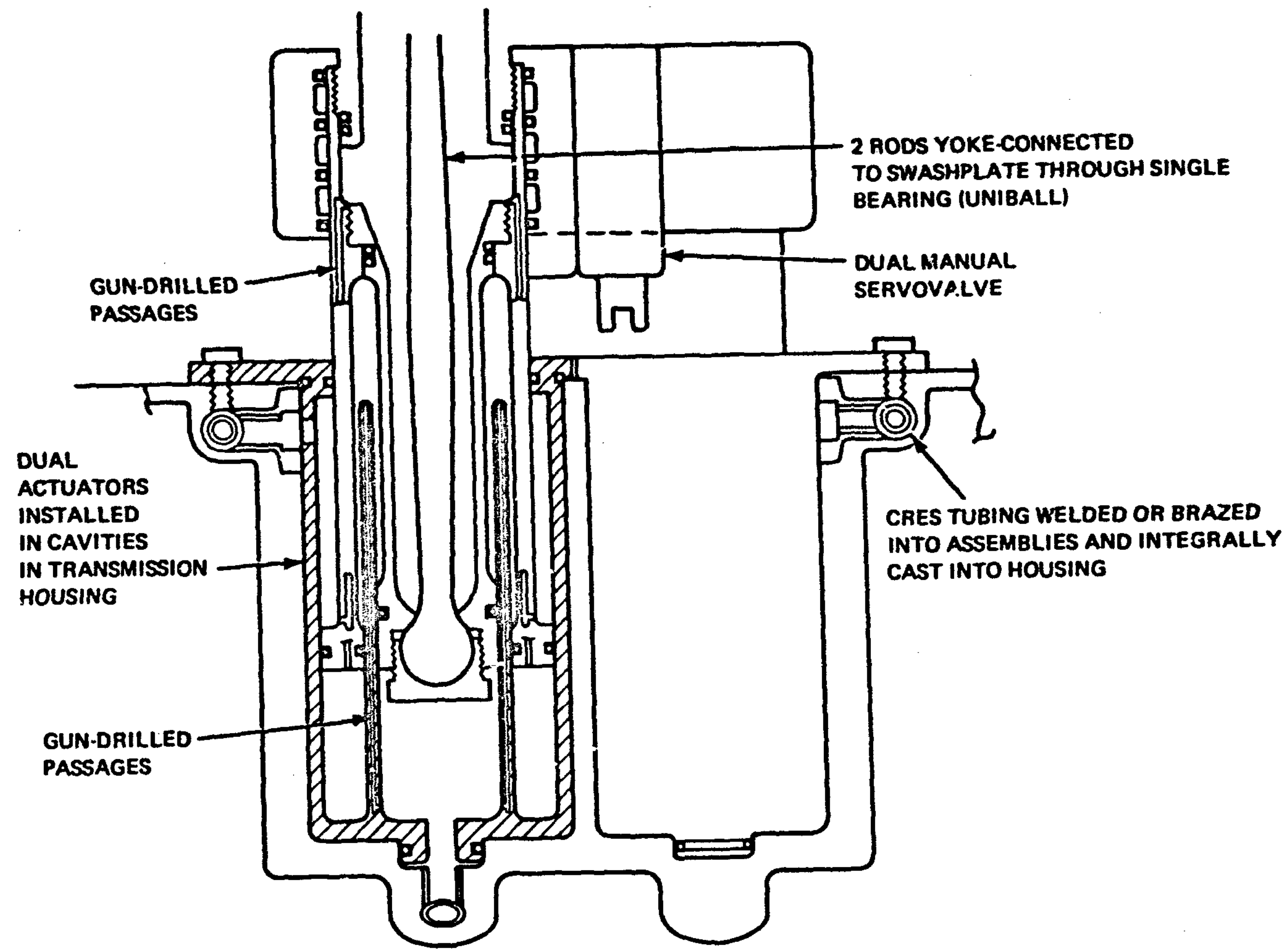


Figure B-5. Rotor Control Actuator Installed in Cover Plate of Cored Transmission.

FOUR-PUMP MODULARIZED FLIGHT CONTROL SYSTEM

For the purpose of concept evaluation, this system can be considered a spinoff from the two-pump modularized system. It would use exactly the same hydraulic rotor-control actuators, but twice as many power generation and control units as the two-pump system. Essentially, there would be dual power-generation and control units at each end of the aircraft. Two variable-delivery pumps would be mounted on each of the forward and aft rotor transmission. Each of these units would be rated at 3000-psi, 8-gpm flow, and other system components would be sized for this reduced flow.

Two reservoir/control modules would be located in the forward pylon area, suitably staggered to meet vulnerability requirements. The rotor-control actuators would be configured and located exactly like those of the two-pump system. The two forward hydraulic systems would supply power to the lower stick-boost and SAS actuators, as well as the rotor-control actuators. The lower control actuators exactly duplicate those of the two-pump system.

The pumps for the two aft systems would be mounted on the aft transmission. One unit would be attached to the AGB and the other to a pad on the side of the transmission. The reservoir/control modules would be located in the aft pylon area or at each side of the transmission, much like the present CH-47C manifolds. In either case, the modules would be staggered in order to reduce vulnerability.

The electrical control and indicating systems would be considerably more complicated than those of the two-pump system. Most of the normal functions would be required for each of the four systems, and therefore, the complexity would be doubled.

ACP CONCEPT EVALUATIONS AND SELECTION

Introduction

The four basic concepts are evaluated in this section. Table B-1 provides a summary of the work. In all areas, except cost, the CH-47C was considered the baseline with a rating of 5 out of 10 points. Each of the concepts being considered was rated relative to the CH-47C and given a higher (than 5) number if it was better and a lower number if it was inferior to the CH-47C design. Cost was the one exception because:

1. The baseline CH-47C system was considerably superior to all others in this area.
2. There was a very large cost spread between the highest and lowest ranking systems.

TABLE B-1. ACP CONCEPT SELECTION SUMMARY

CONCEPT	RELIABILITY	MAINTAINABILITY	SAFETY	VULNERABILITY	COST	WEIGHT	TOTAL POINTS	OVERALL 0-10 RATING
IAP	8	10	9	5	2	1	35	5
CORED TRANSMISSION	9	9	8	8	0	3	37	5
MOD.+ PTU	10	10	10	8	8	6	52	10
DUAL MOD	9	7	6	8	6	4	40	7
CH-47C	5	5	5	5	*10	5	35	5

* Used 10 instead of 5 because CH-47C decidedly superior and because of the large spread between highest and lowest rated system concepts.

Reliability

Tables B-2 through B-5 show the reliability evaluation of each concept. All were rated higher than the CH-47C, but the IAP and dual modularized systems were downgraded because of complexity. The radically advanced nature of the cored transmission concept and doubts as to manufacturing ease detracted from an otherwise high rating.

Maintainability

Tables B-6 through B-9 show the maintainability evaluation of each concept; once again, all scored relatively high. The dual modularized system was downgraded because of its complexity. Like the IAP system, its complexity was expected to result in reduced access in the forward and aft rotor areas. The cored transmission concept was downgraded for two major reasons. With its hydraulic components buried in (and driven by) the transmissions, servicing and inspection was expected to be difficult, and ground checkout nearly impossible.

Safety

Tables B-10 through B-13 show the safety evaluation of each concept. The dual modularized system was downrated because its complex and congested systems fore and aft were expected to present safety problems in the form of "Murphy" potential and poor inspectability.

Vulnerability

Table B-14 provides an outline of the vulnerability evaluation. All of the systems were equally rated except for the IAP. Its concentrated components provided areas with high probability of single-hit kills, yet those areas would be difficult to shield with armor.

Cost

Table B-15 provides a summary of concept cost. The complexities of the IAP, cored transmission, and dual modularized systems all tended to increase system costs. The IAP and cored transmission were even more costly because of their requirements for advanced technology.

TABLE B-2. RELIABILITY EVALUATION OF INTEGRATED ACTUATOR PACKAGE

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
LEAK POINTS	5	10	4	20	40	MIN POSSIBLE
HOSE/TUBE QUANTITY	5	10	3	15	30	MIN POSSIBLE
SYSTEM COMPLEXITY	5	2	4	20	8	EXTREMELY COMPLEX, WITH MULTIPLE PUMPS AND CONTROLS
STATE OF THE ART	5	2	3	15	6	ADVANCED, MULTIPLE UNITS AFFECT RELIABILITY
RESISTANCE TO VIBRATION-INDUCED FAILURES	5	6	4	20	24	SUBJECT TO ROTOR PER REV VIBS, BUT COMPACTNESS OF CONFIG. MAKES BETTER THAN CH-47C
RESISTANCE TO MAINTENANCE-INDUCED FAILURES	5	8	2	10	16	NEARLY AS GOOD AS CORED XMSN BUT WT AND SPACE DICTATES MORE PROJECTIONS
RESISTANCE TO MANUFACTURING, STORAGE, AND HANDLING DAMAGE	5	1	1	5	2	VERY COMPLEX; SUBJECT TO DAMAGE
ADJUSTMENTS				-	+12	LESS CONTAMINATION (4X3)
CH-47C OVERALL RATING				105		
CONCEPT OVERALL RATING					138	

TABLE B-3. RELIABILITY EVALUATION OF CORED TRANSMISSION

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
LEAK POINTS	4	10	4	20	40	MIN POSSIBLE
HOSE/TUBE QUANTITY	5	10	3	15	30	MIN POSSIBLE
SYSTEM COMPLEXITY	5	7	4	20	28	NO MORE COMPLEX THAN CH-47C; SYSTEM IS MODULARIZED
STATE OF THE ART	5	1	3	15	3	VERY ADVANCED, R WILL BE POOR FOR SOME TIME
RESISTANCE TO VIBRATION-INDUCED FAILURES	5	5	4	20	20	XMSN WILL TEND TO DAMP A/F VIB, BUT COULD BE THE SOURCE OF OTHER VIB PROBLEMS
RESISTANCE TO MAINTENANCE-INDUCED FAILURES	5	9	2	10	18	ALL PLUG-IN MOCULES WITH PROPER DESIGN. LITTLE CHANCE FOR THIS PROBLEM
RESISTANCE TO MANUFACTURING, STORAGE, AND HANDLING DAMAGE	5	1	1	5	1	VERY COMPLEX MODULES; SO VERY SUSCEPTIBLE
ADJUSTMENTS				-	8	LESS CONTAMINATION THAN 47C BUT MORE THAN IAP (4 x 2)
CH-47C OVERALL RATING				105		
CONCEPT OVERALL RATING					148	

TABLE B-4. RELIABILITY EVALUATION OF MODULARIZED SYSTEM WITH PTU THIRD SYSTEM

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
LEAK POINTS	5	7	4	20	28	REDUCED LEAK POINTS, BUT TUNNEL RUNS STILL IMPACT
HOSE/TUBE QUANTITY	5	7	3	15	21	SIMILAR TO ABOVE
SYSTEM COMPLEXITY	5	7	4	20	28	VERY STRAIGHTFWD SYSTEM; MOST COMPLEXITY FROM TUBE RUNS
STATE OF THE ART	5	10	3	15	30	VERY WELL-PROVEN CONCEPT
RESISTANCE TO VIBRATION-INDUCED FAILURES	5	6	4	20	24	SIMILAR TO CH-47C, BUT W/MODULE AND LESS TUBE RUNS
RESISTANCE TO MAINTENANCE-INDUCED FAILURES	5	6	2	10	12	SAME AS ABOVE
RESISTANCE TO MANUFACTURING, STORAGE, AND HANDLING DAMAGE	5	7	1	5	7	EXCEPT FOR MODULES, WOULD HAVE SCORED HIGHER
ADJUSTMENTS				-	4	SLIGHTLY LESS CONTAMINATION POTENTIAL (4 x 1)
CH-47C OVERALL RATING				105		
CONCEPT OVERALL RATING					154	

TABLE B-5. RELIABILITY EVALUATION OF MODULARIZED SYSTEM WITHOUT PTUs, TWO SYSTEMS EACH, FORE AND AFT

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
LEAK POINTS	5	7	4	20	28	EXTRA SYS'S CAUSE SAME NUMBER LEAK POINTS AS 2-PUMP MOD SYS
HOSE/TUBE QUANTITY	5	8	3	15	24	AS ABOVE, FOR HOSE AND TUBE, QUANTITY
SYSTEM COMPLEXITY	5	4	4	20	16	FEWER HOSES, BUT EXTRA PUMPS AND CONTROL UNITS
STATE OF THE ART	5	10	3	15	30	VERY WELL-PROVEN COMPONENTS
RESISTANCE TO VIBRATION-INDUCED FAILURES	5	5	4	20	20	WOULD HAVE SURPASSED CH-47C BUT FOR EXTRA PUMPS AND CONTROLS
RESISTANCE TO MAINTENANCE-INDUCED FAILURES	5	6	2	10	12	SIMILAR TO CH-47C BUT WITH MODULE AND FEWER LINE RUNS
RESISTANCE TO MANUFACTURING, STORAGE, AND HANDLING DAMAGE	5	6	1	5	6	EXCEPT FOR MULTIPLE MODULES, WOULD HAVE SCORED HIGHER
ADJUSTMENTS				-	+4	LESS CONTAMINATION (4 x 1)
CH-47C OVERALL RATING				105		
CONCEPT OVERALL RATING					140	

TABLE B-6. MAINTAINABILITY EVALUATION OF INTEGRATED ACTUATOR PACKAGES

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
PREVENTIVE MAINTENANCE						
INSP FREQ AND EASE	5	10	4	20	40	- SAME INSP FREQ. COMPACT, MULTIPLE INSP AREAS
SERVICE FREQ AND EASE	5	10	3	15	30	- 2 MAJOR FILL AREAS BUT EACH AREA HAS 2 FILL POINTS (EACH DUAL)
TUBES AND HOSES ADJUST	5	10	2	10	20	- MIN POSSIBLE, NO HOSES
FLUID LEVEL CHECKS	5	3	3	15	9	- PHYSICAL CK INVOLVES MULTIPLE POINTS. REMOTE INDICATORS
ADJ/CALIB REQUIREMENTS	5	5	4	20	20	- SAME
				80	119	
FAULT CORRECTION						
DIAGNOSTICS	5	7	4	20	28	- CD AND TEMP SENSORS
FAULT ISOLATION AREA	5	10	4	20	40	- VERY COMPACT
ACCESS POTENTIAL	5	5	4	20	20	- CLEAR ACCESS COMPROMISED BY TIGHTNESS IN AREA OF ACTUATORS
STD TEST EQUIP	5	1	3	15	3	- WILL REQUIRE SPECIAL TEST SET TO C TROUBLESHOOT IAP
GEN. RR REQUIREMENTS	5	8	2	10	16	- PLUG-IN UNITS A BONUS. CONFINED AREA OF IAP HINDERS SAME
QUICK DISCONNECTS;	5	8	2	10	16	- MOST ITEMS HAVE QD
SYS GND CKOUT CAP.	5	10	4	20	40	- ALL SYS CAN BE CHECKED OUT ON GND W/O PWR CART
				115	163	
ADJUSTMENTS				-	-	IF USE XMSN FLEX DRIVE, DEDUCT 36 POINTS FROM IAP (4 x 1) FOR GND CK
CH-47C OVERALL RATING				209		
CONCEPT OVERALL RATING					282	

TABLE B-7. MAINTAINABILITY EVALUATION OF CORED TRANSMISSION

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
PREVENTIVE MAINTENANCE						
INSP FREQ AND EASE	5	8	4	20	32	- COMPACT, SIMPLE INSP AREAS. SAME FREQ OF INSP
SERVICE FREQ AND EASE	5	3	3	15	9	- 2 MAJOR FILL AREAS, BUT EACH AREA HAS 2 FILL PTS.
TUBE AND HOSE ADJUST	5	10	2	10	20	- MIN POSSIBLE NEED FOR ADJUSTMENTS
FLUID LEVEL CHECKS	5	7	3	15	21	- MUST CLIMB TO PHYSICALLY CK, BUT DOES HAVE REMOTE INDICATOR
ADJ/CALIB REQUIREMENTS	5	5	4	20	20	- SAME
				80	102	
FAULT CORRECTION						
DIAGNOSTICS	5	7	4	20	28	- INCLUDES PUMP ΔP IND AND SYS TEMP IND
FAULT ISOLATION AREA	5	10	4	20	40	- MIN AREA
ACCESS POTENTIAL	5	7	4	20	28	- CLEAN INST'L BUT SIZE OF MODULES A BURDEN IN XMSN AREA
STD TEST EQUIP	5	5	3	15	15	- SAME
GEN RR REQUIREMENTS	5	9	2	10	18	- CLEAN, SIMPLE MODULE REMOVALS. POSSIBILITY OF SOME CONGESTION IN AREAS
QUICK DISCONNECTS	5	9	-	10	18	- MOST PLUG-IN UNITS HAVE QD
SYS GNI CKOUT CAP	5	1	4	20	4	- VERY POOR; EACH XMSN MUST TURN TO PWR HYD SYS MUST USE GND PWR UNIT
				115	151	
ADJUSTMENTS				-	-	NONE
CH-47C OVERALL RATING				209		
CONCEPT OVERALL RATING					253	

TABLE B-8. MAINTAINABILITY EVALUATION OF CH-47 MODULARIZED SYSTEM WITH PTU

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
PREVENTIVE MAINTENANCE						
INSP FREQ AND EASE	5	6	4	20	24	- SAME FREQ. MORE COMPACT INSP AREAS BUT LONG RUNS
SERVICE FREQ AND EASE	5	10	3	15	30	- CENTRAL POINT SERVICING
TUBE AND HOSE ADJUST	5	7	2	10	14	- MUCH REDUCED FROM H-47C, STILL HAVE LONG RUNS, BUT LESS CONGESTION.
FLUID LEVEL CHECKS	5	7	3	15	21	- MUST CLIMB TO PHYSICALLY CK, BUT HAS REMOTE IND
ADJ/CALIB REQUIREMENTS	5	5	4	20	20	- SAME
				80	109	
FAULT CORRECTION						
DIAGNOSTICS	5	7	4	20	28	- INCLUDES PUMP ΔP IND AND SYS TEMP IND
FAULT ISOLATION AREA	5	8	4	20	28	- MORE COMPACT SYSTEM HAVING FEWER UNITS
ACCESS POTENTIAL	5	7	4	20	28	- RELATIVELY CLEAN MODULE INST'L, PLUS FLEXIBLE MODULE LOCATIONS
STD TEST EQUIP	5	5	3	15	15	- SAME
GEN. RR REQUIREMENTS	5	8	2	10	18	- CLEAN MODULE RR, BUT DEGRADED BY LINE RUNS REMAINING
QUICK DISCONNECTS	5	7	2	10	14	- MODULE PLUG-IN UNITS ACCOUNT FOR MOST IMPROVEMENT
SYS GND CKOUT CAP	5	9	4	20	36	- GOOD TWO-SYSTEM CK OUT - MAIN PUMP NOT CK'D BUT THIS COULD ADD TO BENEFITS
				115	167	
ADJUSTMENTS				-	-	NONE
CH-47C OVERALL RATING				209		
CONCEPT OVERALL RATING					276	

TABLE B-9. MAINTAINABILITY EVALUATION OF DUAL MODULARIZED SYSTEM (TWO SYSTEMS EACH, FORE AND AFT)

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
PREVENTIVE MAINTENANCE						
INSP FREQ AND EASE	5	6	4	20	24	- SAME INSP FREQ. MULTIPLE INSP AREAS
SERVICE FREQ AND EASE	5	3	3	15	9	- SAME FREQ. 2 MAJOR AREAS WITH 2 FILLS EACH AREA
TUBE AND HOSE ADJUST	5	8	2	10	16	- MUCH SIMPLER THAN CH-47C. SHORTER RUNS, BUT CONGESTED AT HEADS
FLUID LEVEL CHECKS	5	6	3	15	18	- HAS REMOTE IND. PHYSICAL CKS INVOLVE MULTIPLE POINTS
ADJ/CALIB REQUIREMENTS	5	5	4	20	20	- SAME
				80	87	
FAULT CORRECTION						
DIAGNOSTICS	5	7	4	20	28	- INCLUDES PUMP ΔP IND AND SYS TEMP IND
FAULT ISOLATION AREA	5	7	4	20	28	- MORE COMPACT AREAS. DUAL FORE AND AFT SYS REDUCES RATING
ACCESS POTENTIAL	5	6	4	20	24	- RELATIVELY CLEAN MODULE INST'L PLUS SOMEWHAT FLEXIBLE LOCATIONS
STD TEST EQUIP	5	5	3	15	1[illegible]	- SAME
GEN RR REQUIREMENTS	5	8	2	10	16	- CLEAN MODULE RRs BUT DEGRADED BY CONGESTION AT HEADS
QUICK DISCONNECTS	5	8	2	10	16	- MODULES HAVE PLUG-IN UNITS, ONLY FEW LINE RUNS
SYS GND CKOUT CAP	5	2	4	20	8	- ONLY NO. 2 SYS CAN BE CK'D OUT W/O GND CART
				115	135	
ADJUSTMENTS				-	-	NONE
CH-47C OVERALL RATING				209		
CONCEPT OVERALL RATING					222	

TABLE B-10. SAFETY EVALUATION OF INTEGRATED ACTUATOR PACKAGE

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
MULTIPLE COMPONENT FSR	5	2	4	20	8	WITH 8 PUMPS AND CONTROLS, HIGH PROBABILITY OF FLIGHT SAFETY MALFUNCTIONS. SEE LEAK POINTS BELOW.
LEAK POTENTIAL	5	10	4	20	40	ALMOST NONE
CONTAMINATION POTENTIAL	5	9	3	15	27	SMALL ISOLATED SYSTEM WITH SMALL RPL ITEMS
"MURPHY" POTENTIAL	5	9	2	10	18	VERY LITTLE WITH ADEQUATE DESIGN
CRITICAL INSPECTABILITY	5	8	3	15	24	EASY TO INSP. WITH MOST ITEMS VISIBLE
SYSTEM DAMAGE POTENTIAL	5	7	1	5	7	PROTRUSIONS PLUS SIZE OF UNIT IN CONFINED AREA INCREASES POTENTIAL
ADJUSTMENTS				-	-	NONE
CH-47C OVERALL RATING				85		
CONCEPT OVERALL RATING					124	

TABLE B-11. SAFETY EVALUATION OF CORED TRANSMISSION

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
MULTIPLE COMPONENT FSR	5	6	4	20	24	TWO SYS EACH, FORE AND AFT, SLIGHTLY DOWNGRADED FOR ACT. TO SWASHPLATE LINKAGE
LEAK POTENTIAL	5	10	4	20	40	LESS THAN ANY OTHER SYS EVALUATED
CONTAMINATION POTENTIAL	5	7	3	15	21	FEWER MODULES, BUT SIZE OF SAME MAKES EASIER TO CONTAMINATE
"MURPHY" POTENTIAL	5	10	2	10	20	ALMOST NO POSSIBILITY
CRITICAL INSPECTABILITY	5	1	3	15	3	ALMOST NONE, BUT SEE ADJUSTMENT BELOW
SYSTEM DAMAGE POTENTIAL	5	8	1	5	8	ALL CONTAINED BUT SOME POTENTIAL WHEN HANDLING
ADJUSTMENTS				-	+6	3 x 2 = 6 ALTHOUGH HARD TO INSP., CONTAINED UNIT SHOULD REQUIRE LESS
CH-47C OVERALL RATING				85		
CONCEPT OVERALL RATING					122	

TABLE B-12. SAFETY EVALUATION OF MODULARIZED SYSTEM WITH PTU THIRD SYSTEM

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
MULTIPLE COMPONENT FSR	5	9	4	20	36	STRAIGHTFWD. DUAL SYS. WITH 3RD SYS. NOT DETRIMENTALLY IMPACTING FLT. SAFETY RELIABILITY
LEAK POTENTIAL	5	7	4	20	28	MODULARIZATION SCORES HIGH, BUT TUNNEL LINE RUNS LOWER SCORE
CONTAMINATION POTENTIAL	5	7	3	15	21	SMALL PLUG-IN UNITS AND MODULE QD AIDS SCORE
"MURPHY" POTENTIAL	5	7	2	10	14	SOME POTENTIAL ELIMINATED AT MODULE BUT LINES AND CK. VALVES LOWER SCORE
CRITICAL INSPECTABILITY	5	7	3	15	15	IMPROVEMENT OVER H-47C DUE TO CLEAN LINE RUNS AND MODULES
SYSTEM DAMAGE POTENTIAL	5	7	1	5	7	IMPROVEMENT DUE TO FEWER LINE RUNS AND "BLOCK" TYPE MODULE
ADJUSTMENTS				-	20	5 x 4 = 20 INCREASED RATING FOR FSR PARTIAL 3RD SYS. BACKUP
CH-47C OVERALL RATING				85		
CONCEPT OVERALL RATING					141	

TABLE B-13. SAFETY EVALUATION OF MODULARIZED SYSTEM WITHOUT PTU, TWO SYSTEMS FORE AND AFT

FACTOR	CH-47C RATING	SYSTEM CONCEPT RATING	WEIGHT 1-4	WEIGHTED CH-47C	WEIGHTED CONCEPT	COMMENTS
MULTIPLE COMPONENT FSR	5	4	4	20	16	4 TOTAL SYSTEMS, BUT MODULARIZATION HELPS SOMEWHAT
LEAK POTENTIAL	5	7	4	20	28	WITH FORE AND AFT SYS, ALL CONNECTING LINES ELIMINATED
CONTAMINATION POTENTIAL	5	7	3	15	21	SMALL PLUG-INS; MODULE WITH QD
"MURPHY" POTENTIAL	5	6	2	10	12	MODULES AND WELDED LINES IMPROVEMENT OVER CH-47C, BUT SOME CONGESTION FORE AND AFT
CRITICAL INSPECTABILITY	5	6	3	15	18	WITH 2 SYS EACH END, SOMEWHAT HIDDEN, COULD BE 7
SYSTEM DAMAGE POTENTIAL	5	6	1	5	6	BASIC DAMAGE POTENTIAL SAME AS MODULE W/PTU SYS. BUT CONGESTION FORE AND AFT INCREASES POSSIBILITY
ADJUSTMENTS				-	-	NONE
CH-47C OVERALL RATING				85		
CONCEPT OVERALL RATING					101	

TABLE B-14. VULNERABILITY EVALUATION OF ACP SYSTEM CANDIDATE CONCEPTS

SYSTEM	RATING	COMMENTS
INTEGRATED ACTUATOR PACKAGE	5	- TOO MANY COMPONENTS WITH RESULTANT POSSIBILITY OF LOSING TWO SYSTEMS - LOSS OF ANY ACTUATOR OR DUAL HYDRAULIC POWER UNIT IS CRITICAL
CORED TRANSMISSION	8	- DETAIL DESIGN OF SYSTEM ELEMENTS COULD EASILY LEAD TO AREAS WHERE ONE ROUND COULD TAKE OUT BOTH SYSTEMS
DUAL MODULARIZED SYSTEM	8	- VULNERABLE AREA IS MINIMIZED WITH EFFECTIVE REDUNDANCY - ADDITIONAL POWER GENERATING ELEMENTS MAKE TOTAL SYSTEM AREA EQUIVALENT TO EXTRA LINES REQUIRED BY NO. 2 SYSTEM
MODULARIZED SYSTEM WITH PTU	8	- THIRD SYSTEM PTU BACKUP IS NOT AN EFFECTIVE WAY OF PROVIDING BALLISTIC PROTECTION. IN MANY INSTANCES BOTH PRIMARY SYSTEMS ARE DISABLED BY HITS, THE THIRD SYSTEM THEN BECOMES USELESS - EFFECTIVE SEPARATION OF SYSTEM COMPONENTS IS MOST CRITICAL FACTOR

TABLE B-15. COMPARATIVE COSTS OF FOUR ACP CONCEPTS

Components	Concept 1 Integrated actuator package Qty	Concept 1 Cost $	Concept 2 Cored transmission Qty	Concept 2 Cost $	Concept 3 CH 47C modularized Qty	Concept 3 Cost $	Concept 3(a) Dual modularized Qty	Concept 3(a) Cost $	Baseline CH-47C Qty	Baseline Cost $
Modules	4	73,902			2/4	12,520	4/4	23,748		
Actuators	(2) 8				(0)(2) 8	18,070	(0)(2) 8	18,070	4	8,573
Reservoir/separator	(2) 8				(1) 2					
Variable displacement pump	(2) 8									
High pressure filter	(2) 8				(1) 2				8	2,736
Check valves	(14) 56				(8) 16				30	2,826
Relief valves	(6) 24				(3) 6					
Pressure switch	(2) 8				(1) 2					
Accumulator	(2) 8				(1) 2				2	720
Pressure transmitter	(2) 8				(1) 2					
Oil cooler	(2) 8				(1) 2				1	600
Pump failure ind. unit	(2) 8				(1) 2					
Thermal switch	(2) 8				(1) 2					
Reservoir fluid	(2) 8				(1) 2					
Level ind. transmitter										
Electrical connector	(4) 16				(2) 4					
Shaft	(2) 8									
Hydraulic cooling fan	(2) 8				(1) 2					
Bleed valve	(2) 8				(1) 2					
Pressure operate valve	(2) 8				(1) 2					
Filter replacement ind.	(2) 8				(1) 2					
Pressure snubber					(1) 2					
Pilot valve, solenoid operator	(2) 8				(1) 2					
Pumps	(2) 8	In modules			2	2,800	4	5,400	2	3,000
Hardware-fittings hoses, clamps, tubing		200				1,761		200		1,761
Misc-switches, connectors, etc.										559
Plumbing install.						1,000				1,000
Total		74,102				36,151		47,418		21,775
Cost rating		5		1		10		8		

NOTES:
(1) ALL COSTS ARE UNBURDENED AND FOR SAME YEAR.
(2) PTUs NOT INCLUDED HERE WILL BE CONSIDERED IF CH-47 MODULARIZED SYSTEM IS IN CONTENTION.
(3) COST FOR CORED (INTEGRAL) TRANSMISSION CONCEPT NOT DETERMINED BECAUSE VIABLE COST DATA BASE NOT AVAILABLE. CONCENSUS IS THAT IT WILL BE HIGHER THAN IAP SYSTEM.
(4) DOLLAR VALUES SHOWN IN TABLE B-15 ARE NOT ACCURATE IN ABSOLUTE TERMS. HOWEVER, EXPRESSED VALUES REFLECT RELATIVELY ACCURATE RATIOS.

Weight

The IAP, cored transmission, and dual modularized systems were at a weight disadvantage because each basically consisted of four complete power and distribution systems. The IAP concept had an additional disadvantage because of its packaging requirements. The cored transmission concept also had a packaging problem that evidenced itself in the transmission envelope.

The concept weight evaluations required that a number of assumptions be made and certain shortcuts effected:

1. CH-47D data was used to establish the weights of CH-47 modularized and dual modularized system components when similarities existed.

2. The stick-boost (lower controls) system was considered similar for all systems and equal in weight to that of the CH-47D.

3. The weight of the CH-47D lower stick boost was used as a calculation basis for all systems.

4. Modularizing a set of components increases the set weight by 15%, due to "filling in" between components.

5. Component weight will vary as the square root of flow rate.

6. Each actuator has a flow rate requirement of 3.75 gpm, or 7.5 gpm per rotor, or 15 gpm per aircraft system.

7. The baseline CH-47C flight control hydraulic system weighs 455 lb without the stick boost. The stick-boost system of the CH-47D is 102 lb, compared to the CH-47C weight of 41 lb. The difference is due largely to the stick-boost actuators, which weigh 32 lb in the 47C and 85 lb in the 47D. To avoid the problem of large weight differences between the CH-47C baseline weight and the concept weights, the stick-boost system weight was deleted.

Integrated Actuator Package Concept

Assuming that the pumps are driven by electric motors, coolers and fans are needed:

Flow rate = 3.75 gpm

Estimated weight of (1) CH-47D module 74 lbs @ 15 gpm

Weight of (1) system mounted on actuator:

$74\left(\frac{3.75}{75}\right)^{.5}$	37	
Motors (est)	6	
Cooler	3	
Fan	2	
Weight per single Act.	48	
Total = 8 x 48 =		384
Actuators installation; estimated same as CH-47C		241
Controls, etc., (increased for complexity) est.		20
		645

Cored Transmission Concept

The current rear transmission is mounted too low to use this concept. For this study, it is assumed the aft transmission is the same as the forward.

Modifying the case to accommodate the concept requires supports and space. Estimate:

10 lb/actuator x 4 =	+40
Remove existing CH-47C actuator supports	-34
Add linkage for swashplate motion actuator x 4 =	+28
Redesign actuators; assume +20 x 4 =	+80

Modules: assume (2) fwd and (2) aft at

$74 \left(\frac{7.5}{15}\right)^{.5} \times 4 =$	209
Actuators less supports (CH-47C)	207
Controls, est	12
	542

CH-47 Modularized with PTU Backup

The actuator weights of the CH-47D are heavier than the CH-47C; hence, the CH-47C actuators are used instead of those of the CH-47D.

CH-47D	454
Less actuators of CH-47D w/o supports, etc.	-231
Plus actuators of CH-47C w/o supports, etc.	+195
	418

CH-47 Modularized with Dual Modules Fwd and Aft

Modules	209
Actuators, CH-47C instl supports, etc.	241
Controls	12
Lines	20
	482

Summary

The ratings, based on estimated system weights, are:

Concept	Weight	Rating
CH-47C	455	5
IAP	645	1
Cored	542	3
Mod + PTU	418	6
Dual Mod	482	4

APPENDIX C

ADVANCED COMPONENT CONCEPTS

INTRODUCTION

During the ACP system design effort, a number of advanced component concepts were considered. These were not included in the final ACP design in order to avoid clouding the basic issue, i.e., determining the relative benefits of 3000-psi and 8000-psi technology. Two concepts were singled out for further investigation in order to:

1. Further explore potential benefits and drawbacks.

2. Determine the development requirements for each concept.

As the investigations progressed, it became evident that the unvented seal concept offered greater potential benefit with fewer drawbacks, and required less development effort.

UNVENTED MULTIPLE SEAL CONCEPT

Introduction

Seal leakage is the overwhelmingly dominant cause of hydraulic servocylinder removals. One study noted that 50% of all U. S. Army helicopter servocylinder removals were the result of leakage (Reference 45). Other studies involving individual Army helicopters have noted similar results (Reference 46).

Considerable cost savings could be realized by eliminating seal leakage. These savings vary with many factors, but the primary determinants are:

1. The number of seal installations per helicopter.

2. The total number of helicopters in the fleet.

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[45]Huffman, J. L., and Dockswell, S., U. S. ARMY HELICOPTER HYDRAULIC SERVOCYLINDER RELIABILITY AND MAINTAINABILITY INVESTIGATION, Systems Associates, Inc.; USAAMRDL Technical Report 73-29, U. S. Army Air Mobility Research and Development Laboratory, Eustis Directorate, Fort Eustis, VA, May 1973.

[46]CH-54A MAIN ROTOR PRIMARY SERVO, USAAVSCOM Technical Report 73-22, U. S. Army Aviation Systems Command, September 1973, AD 767539.

3. The fleet flight activity.

A study of U. S. Army helcopter hydraulic servocylinders estimated that, for a fleet of 1833 UH-1H helicopters, annual cost savings of between $2,879,822 and $3,664,860 would be realized if leakage problems were eliminated (Reference 45). Assuming a particular seal reliability improvement involved only new materials or the use of non-radical configurations, it would be relatively easy to apply the new technology to nearly the entire Army helicopter fleet and obtain huge cost benefits.

Third generation helicopter hydraulic system servocylinders have evolutionary seal improvements. One example is the "T" seal configuration. These seals have produced significant MTBF improvements in commercial fixed-wing applications, and in UH-1H test actuators (Reference 45). Boeing Vertol has successfully used the "T" seal in various helicopters. In CH-47C applications no quantitative data has been compiled. The Boeing Vertol YUH-61A rotor control actuators utilize "T" seals, and there have been no actuator seal failures in approximately 3500 hours of contractor and Army testing of three aircraft. Although these third generation system seals do not promise quantum reliability improvements, improvements of 20% to 50% are potentially achievable and obvious LCC benefits could be realized.

A seal concept that has been used by the Russians in at least some fighters (MIG 21 and Su 7) may be applicable to helicopter hydraulic systems and could provide a quantum increase in reliability. The Russians simply install seals (O-rings in this case) without providing any return system drains. MIG afterburner actuators are equipped with three O-rings as an external seal assembly (See Figure C-1). When a used actuator was examined, the innermost ring showed considerable wear, the middle O-ring showed some very slight wear marks, while the outer O-ring (the actual external seal) was in perfect condition (Reference 44).

The success of these Russian seal assemblies apparently disproves one of the ground rules that the entire hydraulics and servo industry in this country has used for quite a number of years. The rule states that one cannot install two seals adjacent to each other without providing a drain to the return systems, because the trapped oil between the seals would form a heat lock which would eventually destroy one of the two seals. Further investigation through the SAE-A6 committee revealed that such a seal blowout actually occurred once during their experiments, but it happened on a dual-seal installation on an actuator piston head, where a rather deep and broad

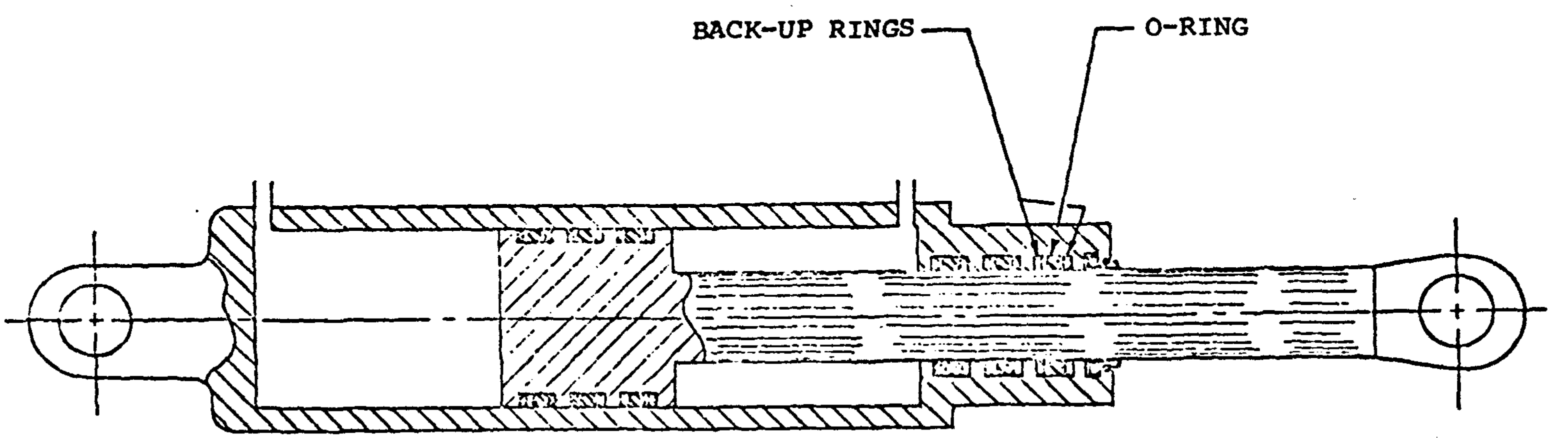

Figure C-1. Typical Actuating Cylinder Incorporating Russian-Type Unvented Seal Installation.

cavity existed between the two seals. The unusually large volume of oil that was therefore trapped between the two seals caused the destruction of one seal. It appears that the previously explained ground rule applies to particular seal installations only. Boeing Vertol has used a dual, unvented seal configuration in CH-47 upper boost actuators since 1960 without encountering any problems. The seal consists of O-rings with Turcon glyd-rings as the rubbing and sealing surfaces. They are used to seal the inner diameter of the piston at the standpipe, and to seal extend pressure from return. The seals operate at pressure differentials that range from 250 psi to 2750 psi over the full flight envelope, with a mean ΔP of 1850 psi at high speed level flight.

Concept Examination

Figure C-2 provides a means to examine this concept in more detail, using one of a number of theories as to how the ventless seals perform. Assuming that the seals are in an actuator that operates at 3000 psi and has a four-way servo ΔP of 1000 psi equally divided between the inlet metering land and the outlet metering land, then the pressure side of the piston will receive 2500 psi during movement and the return side will be subject to 500 psi pressure. Thus, as the rod extends through the shaft seal, it is subject to a pressure from within of 500 psi. Conversely, when the rod is retracting through the seal gland, the internal pressure against the seal is 2500 psi. Since O-rings exhibit less leakage at higher pressures than at low pressures (hence the leakage test requirement for hydraulic equipment to be checked at 5 psi as well as operating pressure), the inner ring, at 500 psi ΔP, will wipe slightly cleaner than the remaining two rings. The fluid that is passed on the rod to the second ring will bypass it and flow to the outer ring. There will only be sufficient oil on the rod to lubricate these rings and none will collect between the seals to build up and trap fluid. It would appear, then, that there may be no pressure buildup between seals when the seals are in good condition. However, if the inner ring has deteriorated to the point where it is passing significant leakage on the extension stroke, it appears that hydraulic fluid would fill the first cavity. When the rod retracts, the pressure is 2500 psi on the inner seal, so there may be no reverse flow. The fluid between the inner and middle seals would remain trapped and could build up to the 2500 psi encountered during the retraction stroke. There would be a point in the degree of wear of the O-ring where it would still seal tightly in the opposite direction from that in which leakage was prevalent. Then, an increase in temperature could cause pressure buildup between the inner seal and the center seal, and there could be a seal blowout. The same condition could occur between the middle seal and the outer seal (assuming the inner seal rather than the middle seal blew out).

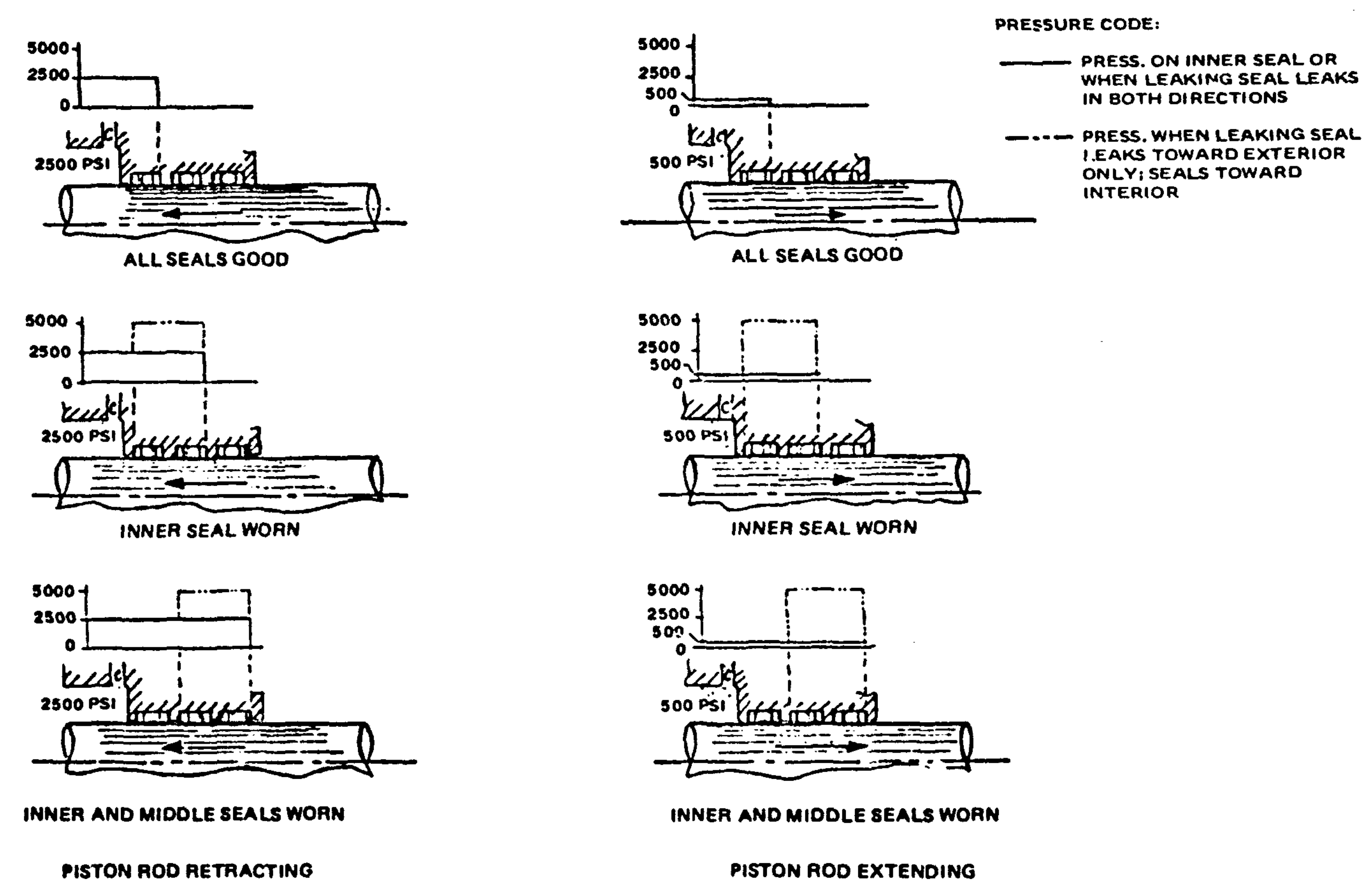

Figure C-2. Pressure Distribution-Multiple Seal Configuration.

From the foregoing it would appear that the vented seal cavity philosophy practiced in this country is well founded, at least during the latter period of seal life. However, it can also be seen that the thermal effects are related to the volume of oil between seals, the relative leakage of the seals, seal compliance, and the susceptibility of seals to failures that are caused by the extrusion gap that is dictated by rod-to-bearing surface diametrical clearance.

The preceeding discussion, concerning the failure mechanism of multiple seal installations, is based on the configuration known to have been used by the Russians, i.e., using "O-rings" as dynamic seals. Today's state-of-the-art configuration requires cap seals along with the "O-rings" to improve basic seal life.

Further Considerations

The unvented multiple seal concept has also been used successfully in production applications by British and French manufacturers, most notably on Hawker Sidley's commercial aircraft, the Trident (Reference 47). In the United States, some experimental testing has been performed by the Vought Corporation, an LTV company (Reference 48). This service experience and testing has indicated that the unvented multiple seal concept can increase seal life and reduce leakage as compared to the vented configurations presently in use. This conclusion is reinforced by Boeing's good service experience on a non-vented dual redundant seal.

The Reference 48 report cites the following several design considerations for optimizing unvented multiple seal performance:

- Uncut back-up rings are superior to scarf cut back-up rings - especially in rod seal applications.
- A tolerance study of rod seal squeeze has been helpful in assuring a minimum squeeze under all conditions. If the dimensions of MIL-P-5514 are to be modified, it is preferable to increase rod diameter rather than reduce groove diameter.
- If cap strips are to be used on a rod, it is important that the inside diameter be an interference fit on the rod.

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[47] Veraar, R., FAIREY FLAT-FACED SERVOVALVE, Presented before SAE A-6 Meeting, October 4-8, 1977.

[48] Fling, K., IMPROVEMENTS IN ACTUATOR ROD, Vought Corp., 1976.

- Reduced clearance between rods and rod bores should be considered when similar materials are used for the barrel and the piston rod.

Development Requirements

Scope

A program should be developed that would allow a more full understanding of the reliability aspects of no-vent multiple seals. An analytical investigation of the following parameters is required:

1. Volume of fluid in the space between the seals.
2. Pressure buildup in the space between the seals due to interseal leakage.
3. Pressure buildup in the space between the seals due to thermal change.
4. Compression effects on the seals due to pressure buildup.

Test Unit

A test actuator would be designed using seal configurations that appear most promising in the areas of minimum leakage and long life. The actuator would be designed to exhibit the same stiffness characteristics as a typical flight controls actuator. It would employ a double-ended rod and double pistons, one set to be the cascaded, unvented seals, while the other set would cascade but be vented to return fluid between seals. These also could be in the form of dual actuators, either tandem or side-by-side. Provisions would be made for instrumenting the volumes between the unvented seals so that accurate pressure values could be determined.

Test Program

The test program should include the following elements:

1. Basic seal configuration tests.

   a. Conduct thermal tests with the actuator static and the spaces between seals filled with fluid. The pressure between seals as the temperature varies.

b. Conduct cycling tests at various rates, as established by a cycling schedule for pilot input and feedback loads over various values of ΔP and temperature. Record the pressure and temperature between seals.

2. Assemble a life-cycle test actuator with new parts and record all pertinent dimensions.

3. Conduct life-cycling tests of the unvented and vented seal configurations simultaneously.

    a. The configurations would be tested simulating the most severe temperature and pressure conditions between the seals that can be anticipated in normal helicopter operations.

    b. The test would require a minimum of 5×10^6 cycles in order to establish useful comparative data.

4. Dismantle the test actuator and inspect the seals, cylinder walls, and rod surfaces, and record their condition. Comparative data on each configuration will be recorded.

5. Prepare a report comparing configurations and providing all test data.

<u>Conclusion</u>

The unvented multiple seal concept offers considerable potential for improving seal life. The aforementioned tests and service experience indicate that MIL-P-5514, which prohibits the redundant, unvented seal, may require modification.

The effects of increased frictional resistance due to the increase in number of seal bearing surfaces is probably insignificant on high-force (swashplate) actuators since the frictional forces are still only a small percentage of the actuator total force capability (Reference 48). For low power applications (e.g., CH-47C lower controls and SAS) the effects of increased friction would have to be considered.

Further investigations should involve the instrumentation of test specimens to learn more about cavity fluid temperatures and pressures under various conditions.

The no-vent multiple seal concept promises a number of benefits, primarily in the areas of reliability and cost. These are:

1. Increased reliability without the necessity of developing exotic seal designs or materials.

2. Reduced machining costs in those cases where vent passages would have to be complex.

3. Elimination of external vent tubes (in some cases). This would provide small improvements in safety, maintainability, vulnerability, and reliability.

4. Decreased material costs.

5. Decreased man-hours required to install an actuator during production.

Besides the questions involving seal blowout, the no-vent multiple seal concept has a few disadvantages, These are:

1. In specific instances, the space required for the multiple seals may limit their number and therefore the reliability that can be attained.

2. Higher friction will result from the multiple seals, but this is not expected to be a problem except (perhaps) for low power applications.

3. A marginal weight increase can be expected.

4. There will be additional machining requirements.

CENTRIFUGAL FILTERS

Introduction

Centrifugal filters are not new. They have been used in various applications, including motorcycle engine lubrication, gas-turbine fuel systems, and the hydraulic systems of certain U. S. Navy ships. Very recently, the NASA Lewis Research Center awarded a transmission gear and bearing lubrication system centrifugal filter study contract to the MAIC Division of Pure Carbon Company, Inc., St. Mary's. Pennsylvania. For several years, centrifugal filters have been successfully used in the lubrication oil systems of diesel truck engines. The truck

filter being used was developed by Glacier Metal Company, Ltd., of England and is manufactured and marketed in the U. S. A. by the Weatherhead Company of Cleveland, Ohio. At this time, Weatherhead does not contemplate qualifying the filter for aircraft systems.

Operation

The filters operate by slinging oil from a rotor that operates at approximately 5000 rpm. The particles of contamination cling to the filter wall and remain there as the lighter, clean oil is exhausted into the sump from the bottom of the rotor. The contaminant will remain on the wall after the system is shut down. The oil is aimed onto the wall via jets that also provide a rotational force to the rotor (Figure C-3).

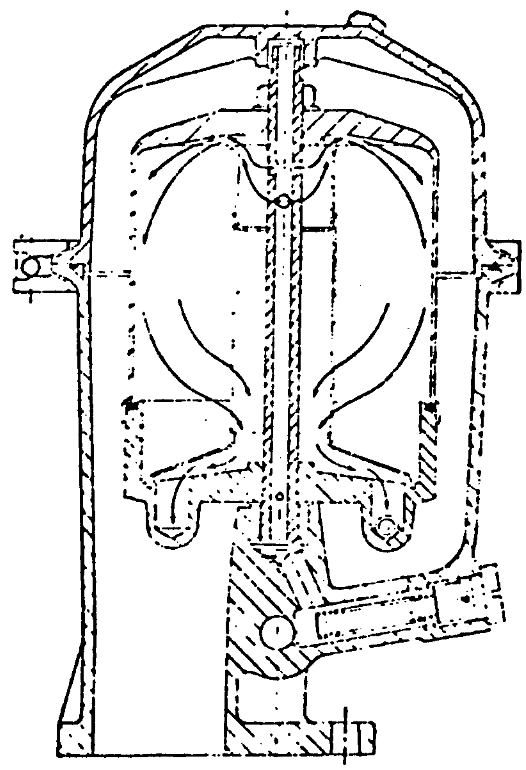
General Information

Although there are several lubrication system filter models available, the following general information is fairly representative of the group:

1. Rotor Speed - 5000 rpm
2. Flow Rate - 2 gpm at approximately 60 psi
3. Pressure drop - 20 to 80 psi
4. Time to operating rpm - 2 min
5. Contaminant storage capacity - 20 in^3 (1 lb)
6. Overall weight - 5 lb

Benefits

Weatherhead claims that filtration ratings of 2 microns (absolute) are easily attained and that particles as small as 0.1 micron are trapped. No filtering element of any sort is used. The contaminant that clings to the inner wall of the filter can be easily removed using a brush and solvent. Additionally, the design allows for large contaminant storage capacity. One unit that is used on diesel engines has a 50-$in.^3$ contaminant storage capacity. It may be possible to design a reasonably-sized hydraulic filter that will not require cleaning during the overhaul life of a helicopter airframe.



CROSS SECTION OF COMPONENTS AND OIL FLOW

Source - Weatherland Company of Cleveland, Ohio, FC-50, Brochure, Undated.

Figure C-3. Internal Operation of Typical Centrifugal Filter.

The diesel engine filters are not used as full-flow units. The filters are normally sized to handle circulation of the diesel engine crankcase 15 times per hour. Tests by Weatherhead and several truck fleets have shown that the centrifugal filter normally requires cleaning once each 80,000 miles, versus the usual 12,000-mile element replacement that the standard full-flow filters require.

The centrifugal filter concept offers a number of benefits to helicopter hydraulic systems, some tangible and some intangible. Most of these benefits are based on two characteristics; the large contaminant-holding capacity and the finer filtration level that may be attainable. In summary, these benefits are:

1. Reduced or zero helicopter downtime for hydraulic filter servicing.

2. Drastic decrease in MMH and spares costs associated with filter maintenance.

3. Complete independence from the supply system for filter servicing. This is important under primitive or combat conditions.

4. Relatively constant pressure drop over the life of a filter, versus the gradually increasing drop of a conventional filter.

5. Ability to extract water from hydraulic fluid.

The centrifugal filter offers marginally finer filtration, i.e., 2 microns absolute versus 3 microns absolute for an off-the-shelf barrier filter. Based on current beliefs regarding acceptable filtration level, this change would have little impact on system reliability. However, investigative work now in progress, as discussed in the state-of-the-art section of this report, could change these beliefs. There are interesting facets to the capabilities of centrifugal filters.

1. The diesel oil filter is capable of 2-micron filtration. If the filter is used for a fluid with a lower specific gravity, a finer filtration level will be obtained. The converse is true for more dense fluids, such as the esters.

2. Rotor speed could be varied to obtain different levels of filtration.

These are areas that could be explored during a test program.

Disadvantages

The centrifugal filter has several disadvantages. The pressure drop required to operate the filter is relatively high; as much as 80 psi in some cases. Another disadvantage is that there is an interval of time between initial system operation and the filter attaining full rpm (and operational efficiency). In the case of diesel engines, that is approximately a 2-minute period.

There is one potential problem that may rule out the centrifugal filter as a candidate for use in helicopter hydraulic systems. In a pressurized return system, the filter sump would be at 50-80 psig instead of the zero-pressure dry sump condition of a diesel installation. In this state, viscous drag might make it impossible to attain proper working rpm by using the pressure drop across the rotor jets. Tests would have to be made to determine if this assumption is correct; if so, it would be necessary to provide rotational power to spin the rotor. This could be accomplished with a small hydraulic or electrical motor, or by "piggy-backing" the filter onto another component to make use of an existing mechanical drive. Although this increases the complexity of the installation, it would provide additional benefits. The positive rotor drive would eliminate the possibility of unknowingly operating for an extended period of time with a disabled filter, as could occur if the rotor were driven only by the pressure drop. It could also eliminate any appreciable delay between system startup and the filter attaining full efficiency. If it becomes necessary to mechanically power the centrifugal filter rotor, the filter will incur substantial weight, acquisition cost, and reliability penalties when compared to standard depth-type filters. The extent of these penalties will be determined by the complexity of the power and drive mechanism.

One unaddressed problem involves the means to determine when the centrifugal filter has reached its contaminant storage capacity. This would have to be considered during the test program outlined below.

Centrifugal filters have a tendency to aerate the fluid during operation. None of the commercially available filters have integral devices to prevent aeration. One centrifugal filter manufacturer believes a solution is available, but does not have funds to independently develop the concept.

Development Requirements

Scope

The overall program would consist of the design and construction of a full-flow centrifugal filter suitable for use in aircraft-type pressurized reservoir hydraulic systems, plus the development of a test program for this filter and for a standard industrial centrifugal filter.

Test Filter

The test filter would consist of a housing, a centrifuge basket, and several forms of centrifuge drive motors, including as a minimum, electric, positive displacement hydraulic, and jet-reaction-type hydraulic. The motors would drive the centrifuge at 5000-rpm minimum rotor speed in a pressurized (50-70 psi) wet sump.

Test Program

The test program would consist of:

1. The acceptance and qualification test requirements of specification MIL F-8815, except that the filtration rate shall be 2 microns absolute.

2. A 5000-hour endurance test program for the dynamic components and seals in a typical hydraulic circuit. These tests will be run on the commercial filter as well as the test filter, unless it becomes obvious early in the test program that the commercial filter cannot function properly in a pressurized reservoir environment.

APPENDIX D

SELECTION OF THE BASELINE HYDRAULIC SYSTEM

INTRODUCTION

This section defines the baseline system selection process. The baseline helicopter flight-control hydraulic system and one selected utility hydraulic subsystem served as vehicles for evaluating three hydraulic system concepts. These concepts were:

1. The baseline 3000 psi hydraulic system.
2. An Advanced Conventional Pressure (ACP) version that reflects the state of the art for approximately the next 10 years.
3. A Very High Pressure (VHP) 8000 psi version.

The three systems, the baseline and its two variations, were compared to determine the benefits and drawbacks offered by each.

Only one utility hydraulic subsystem was studied, because man-hour constraints prohibited investigating all the many subsystems that are used on U. S. Army helicopters. However, the final phase of this report related the benefits/drawbacks of the ACP and VHP concepts to various utility functions such as power steering, wheel braking, cargo ramp actuation, APU start, main engine start, and cargo winch operation.

BASELINE SELECTION PROCESS

The hydraulic system of the CH-47C was selected as the study baseline predicated on the following:

1. It is a first-line U. S. Army helicopter.
2. It is representative of a class that the Army has procured in large numbers and can be expected to procure in equally large numbers in the future.
3. The aircraft will not bias the study in favor of VHP or ACP systems because of unusually high or low system flow rates and/or long or short line runs.
4. It has at least one utility hydraulic system function that is common to most Army helicopters and which provides an adequate base for comparing VHP and conventional pressures.

5. Documented reliability and maintainability operational data is available.

6. Drawings, stress load information,flows, etc., are readily available at Boeing Vertol.

The program Statement of Work (SOW) noted that an Army helicopter hydraulic system was to be the baseline. With out-of-production helicopters eliminated from consideration, the field was narrowed to those helicopters listed in Table D-1. The study in Table D-1 indicated the CH-47C was the most logical baseline choice, but a decision was made to perform a quantitative study to compare the CH-47 against the YUH-61A, which placed second in the initial study. Table D-2 is a distillation of the second study. Once again, the CH-47 rated higher.

A rescue hoist system was selected as the most common utility-type function to be found on helicopters. The YUH-61A has a rescue hoist system, but it is electrically powered. The CH-47 has a hydraulic rescue hoist system; however, it was designed to a 600-lb load, 100-ft/min cable speed, and 100-ft cable lift requirement. The baseline, ACP, and VHP hoist systems were redesigned for a 600-lb load at a cable speed of 300 ft/min with 250 ft of lift. This change was made for two reasons:

1. The revised requirement was more representative of recent rescue hoist designs.

2. VHP technology was expected to prove most advantageous in applications where 3000-psi systems require 10-gpm (and higher) flows. The 300-ft/min requirement resulted in a 3000-psi system flow rate of about 6 gpm. This change facilitated extrapolating study results over the normal spectrum of Army helicopter hydraulic system flow rates.

TABLE D-1. INITIAL STUDY FOR SELECTION OF BASELINE HYDRAULIC SYSTEM

CONSIDERATIONS	ARMY HELICOPTER MODELS (IN PRODUCTION OR DEVELOPMENT)									
	UH-1*	CH-6A	CH-47*	CH-54*	OH-58*	YUH-60A (UTTAS)	YUH-61A (UTTAS)	XCH-62 (HLH)	YAH-63 (AAH)	YAH-64 (AAH)
REPRESENTATIVE HELICOPTER CLASS	YES		YES	NO	YES	YES	YES	NO	YES	YES
WILL NOT BIAS STUDY	NO[1]	DOES NOT HAVE HYDRAULIC SYSTEM	YES[3]	YES	NO	N/A	YES	NO[8]	N/A	N/A
ADEQUATE SPACE	NO[2]		YES[4]	YES[2]	N/A	N/A	YES[7]	YES	N/A	N/A
REPRESENTATIVE UTIL HYD SUBSYSTEM	NO		YES	NO[6]	NO[2]	N/A	NO[6]	NO	N/A	N/A
ADEQUATE R&M DATA	YES		YES	YES	YES	YES	YES	YES	YES	YES
DWGS. AND SPECS READILY AVAILABLE	NO		YES	NO	NO	NO	YES	YES	NO	NO
THIRD GENERATION SYSTEM	NO		YES[5]	NO	NO	YES	YES	YES	YES	YES

* = VARIOUS MODELS CONSIDERED
1 = LOW SYSTEM FLOW RATES
2 = NOT VERIFIED
3 = LONG LINE RUNS, CONVENTIONAL PRESS. REDESIGN WILL NEGATE THIS FACTOR
4 = REQUIRES SKIN MODIFICATIONS
5 = CH-47 MODERNIZATION PROGRAM, SEE TEXT
6 = APU START, SEE TEXT
7 = REQUIRES MAJOR MODIFICATION
8 = HIGH SYSTEM FLOW RATES

TABLE D-2. FINAL STUDY FOR SELECTION OF BASELINE HYDRAULIC SYSTEM

RATING: 0 = UNACCEPTABLE
4 = FULFILLS ALL REQUIREMENTS
16 = TOTAL

CONSIDERATIONS (UNWEIGHTED)	H-47C	YUH-61A	NOTES
DOES NOT BIAS STUDY	4	3	H-47 FLIGHT CONTROL SYSTEM FLOWS IN MID-RANGE
ADEQUATE SPACE FOR POWER-PACK MODULES	2	1	YUH-61A LIMITED IN LONGITUDINAL AND VERTICAL AXIS OF FLIGHT-BOOST ACTUATORS
AT LEAST ONE UTILITY HYDRAULIC SUBSYSTEM COMMON TO ARMY HELICOPTERS	2	1	YUH-61A HAS ONLY APU START AND AIRCRAFT KNEELING H-47 HAS APU START, HOIST, PLUS OTHER MORE COMMON SUBSYSTEMS
ADEQUATE R&M DATA AVAILABLE	4	3	YUH-61A DATA IS PREDICTED
	12/16	8/16	